MODELLING OF TERRESTRIALISATION AND TECHNOLOGY TRANSFER TO ENABLE MANAGEMENT OF KRUGER NATIONAL PARK RIVERS

by

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EXECUTIVE SUMMARY

MOTIVATION AND RATIONALE

In South Africa, flow regimes of rivers that traverse the Kruger National Park (KNP) are expected to change in response to catchment developments outside and upstream of conservation areas. These developments will have ongoing consequences for heterogeneity within riparian zones. One of these consequences may be the encroachment of terrestrial species into the riparian zone, which may be detrimental to riparian species and could reduce both heterogeneity and diversity.

Changes in land use have affected river catchments in most countries (Pettit and Froend, 2001). However, riparian zones in semiarid areas are particularly sensitive to water level changes, and declines in groundwater levels can result in reduced abundance of riparian vegetation (Stromberg *et al.*, 1996). Development (forestry and agriculture) in the Sabie River catchment has resulted in an altered flow regime, and has caused much concern regarding the geomorphological and ecological functioning of the river (van Coller and Rogers, 1996). The Kruger National Park occurs downstream of developments, and as the majority of the Sabie River's water comes from the upper catchment, it is directly affected (van Coller and Rogers, 1996). The question of importance that we addressed was whether future river regulation or natural change will favour encroachment by terrestrial species in the riparian zone, and whether these compositional changes will be within the KNP management objectives.

AIMS AND OBJECTIVES

The overall aim of the project was to engage research, prediction, technology transfer and monitoring through rule based modelling (RBM), to enable effective management of riparian system response to changes in flow regime.

To achieve this aim, the following specific objectives were pursued:

1 Transferal and implementation of the *Breonadia* Model (MacKenzie *et al.*, 1999) to Kruger National Park management. This model services the management goal [Threshold of Probable Concern (TPC)] to reduce the loss of bedrock influence on the Sabie River.

2. Implementation of a structured monitoring programme to provide data for using the *Breonadia* Model to test the TPC set by Kruger National Park (KNP) management.

3. a) Conversion of existing conceptual models to address another TPC, that of terrestrialisation of the riparian zone, into an operational rule based model (RBM).

   b) Transferal of the RBM to KNP management.

   c) Design and implementation of a monitoring programme for testing the RBM.

4. a) Identification of problems associated with the transfer of this predictive technology into the strategic adaptive management (SAM) process being instituted by KNP management

   b) Use of the understanding gained from the project to develop a protocol of technology transfer for use in strategic river management by other river managers and catchment user groups.

ACHIEVEMENT OF STATED OBJECTIVES

Transfer and implementation of the *Breonadia* Model

A second version of the *Breonadia M*odel was installed on computers in Scientific Services at Skukuza, and was also made available for download from the Internet at http:/www.wits.ac.za/cwe/kruproj.htm#rbm. Would be users of the model were trained to use the model and interpret its outputs.

Implementation of a monitoring programme for using the *Breonadia* Model

The TPC for the loss of bedrock influence is that *B. salicina* displays a negative J-shaped curve in its population size structure for all non-germinant established individuals, in the rapid sections of pool-rapid channels (MacKenzie *et al.*, 1999).

Results of monitoring in 2000, 2001 and 2002 showed that in both bedrock anastomosing and pool-rapid channels the population structure was opposite of a negative-J curve. This was due to the effect of the floods of February 2000, which removed the majority of juveniles. The *Breonadia* TPC was thus exceeded, as predicted by the model when a "catastrophic" flood occurs (MacKenzie *et al.*, 1999).

The results of two years of monitoring revealed that *Breonadia* populations in pool-rapid channels were severely damaged by the flood, and would take more than two years to recover. Populations within bedrock anastomosing sections, however, were less seriously affected, and would be able to recover more rapidly. We therefore decided to use only the bedrock anastomosing sites as permanent monitoring sites. We also recommend that the TPC be assessed in bedrock anastomosing channels and not pool-rapid channels.

Data collected from the three years of monitoring were intended for testing and refining the model. However, the magnitude and effect of the 2000 floods reduced the efficiency with which this was possible. The 2000 flood was categorized as a catastrophic flood in the *Breonadia* Model. The TPC was thus predicted to be exceeded for four years, which was shown to be true for the three years in which monitoring was performed. However, this means that limited testing of the model was possible. It is essential that monitoring be continued over the long term, to allow the model to be validated and refined.

Development and transfer of the Terrestrialisation Model

The life cycles of key riparian and key terrestrial species are the two main biotic components of the Terrestrialisation Model (Figure i). The life cycles of each group include germination on available sites, establishment and persistence of individuals, and feedback via propagule production, dispersal and dormancy. Each stage of the life cycle of the two groups is influenced by key processes, these being availability of water from the water table, flow frequency, precipitation, herbivory, and competition. The degree of influence of these processes will depend on the individual's position along a gradient of flow frequency and water availability, whether the individual is riparian or terrestrial, and its life stage or size class.

The interaction of key riparian and terrestrial species with these five processes will result in differential establishment and persistence of individuals of riparian and terrestrial species along a gradient of flow frequency and water availability in the riparian zone. Resulting response curves along this gradient can therefore be established for key riparian and terrestrial species (Figure i). These two response curves provide the basis for calculating the ratio of terrestrial relative to riparian species, which can be used to audit the TPC.

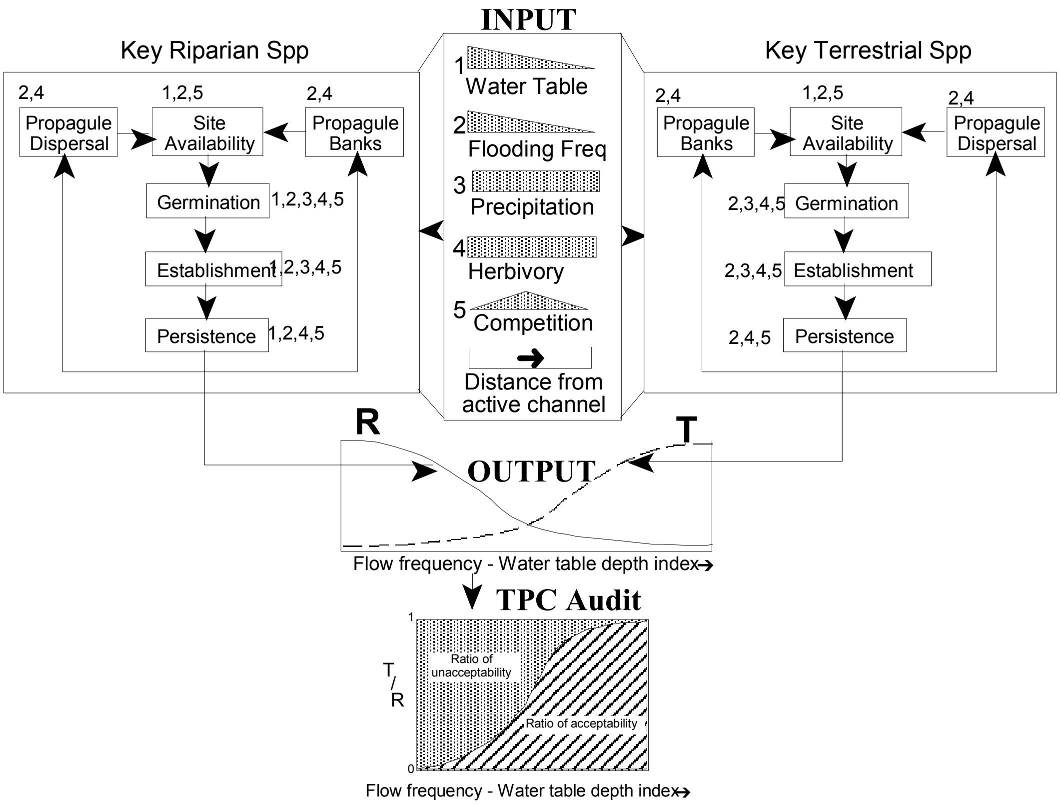

Figure i. Conceptualization of the pragmatic model for the TPC of terrestrialisation of the riparian zone. Inputs and outputs of the model are shown. The numbers in the key riparian and terrestrial species boxes correspond to the numbers in the input box. T and R are terrestrial and riparian species respectively.

We conceptualized modelling the dynamics of key riparian and terrestrial species as modularized population models (Figure ii). The advantages of modularization are well known (Acocks and Reynolds, 1997) and it lends itself well to Visual Basic, which was used for coding the model. Physical environmental variables for each population are rainfall and hydrology, which affect site quality. Site quality determines the success of germination, mediates growth and survival, and affects dispersal. Dispersal may contribute directly to germination or maintain seed banks. Biotic interactions that are important for growth, survival and dispersal are herbivory and competition.

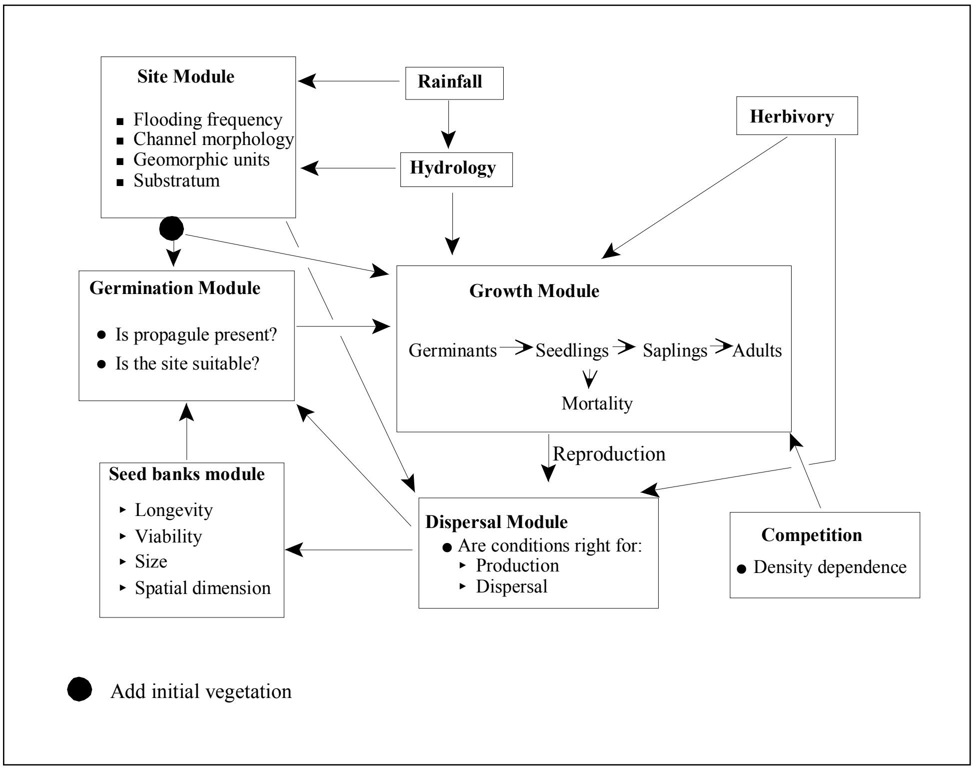

Figure ii. Conceptual model of population dynamics for each key species in the terrestrialisation TPC. Boxes represent modules in the model, and arrows represent inputs, feedbacks and processes.

The Terrestrialisation Model is a modularised, spatially explicit, individual- and rule-based population model of four key species that occur in the riparian zone of rivers in the Kruger National Park. Modules operate as distinct entities with individual internal structure, and communication between modules occurs as inputs from and outputs to other modules (Figure ii).

Setting and Evaluating the TPC

At the outset of this project, 4 key species were selected to work on; 2 riparian and 2 terrestrial. These four species occur over the full range of features on the macro-channel floor, but have distinctly different optima of where they occur. This means that the total T:R ratio (total referring to a ratio incorporating active, seasonal and ephemeral features) will lack resolution and always underestimate the problem of terrestrialisation since it most markedly occurs on ephemeral features, and especially the macro-channel bank. A low T:R ratio may therefore occur due to high numbers of riparian individuals on active and seasonal features, whereas high numbers of terrestrial individuals occur on ephemeral features, effectively masking the problem of terrestrialisation on ephemeral features.

For this reason we have determined to set the TPC (in the form of T:R ratio limits) separately for active, seasonal and ephemeral features so that the TPC audit is conducted along a categorised flow frequency gradient. In this way the problem of terrestrialisation, if it exists or comes into being, can be monitored in reasonable detail. We have also determined to set the TPC for adult populations only. This is due to high volatility and low survival in the numbers of juveniles which makes using them to monitor trends more risky than using the more stable adult populations.

It is apparent from the scenario evaluation (Section 6.3) that on ephemeral features where terrestrialisation is most problematic, the T:R ratio declines during wetter periods and increases during dryer periods. It follows that the oscillation and pattern of wet and dry periods will determine whether the ratio increases or decreases indefinitely, or is dynamic about some check level.

In response to a "natural" scenario, the T:R ratio reaches a maximum of 6 at the end of a period of 60 years (Figure 6.4D), whereas the ratio never goes as high as 0.8 in the wetting scenario, and continues to decline over the 60 years (Figure 6.6D). In response to the drying scenario the T:R ratio gradually increases over the first 50 years, after which the increase becomes more rapid (Figure 6.5D). This exponential increase phase begins at a T:R ratio of about 6. However, the measured T:R range for ephemeral features was 8 to 11 from 2000 to 2002.

Using the drying scenario and at a T:R ratio of 6 (predicted value), the TPC would be exceeded by year 51, whereas at a ratio of 8 (measured value) the TPC would be exceeded by year 55 (Figure 6.5D). That is only 4 unnoticed years of terrestrialisation if a ratio of 8 rather than 6 was used as the TPC for ephemeral features. This difference of 4 years, as well as the point at which exponential increase in the T:R ratio on ephemeral features occurs, was additionally tested in two more drying scenarios: one where ACRU flow data (Schulze, 1995) were reduced by 1.5% per year, and the other similarly by 2%.

In response to the 1.5% drying scenario the T:R ratio reached 6 by year 50 and 8 by year 51, the difference being 3 years less than in response to the 1% drying scenario. By comparison with the 1% drying scenario, a T:R ratio of 6 also marked the exponential increase phase, but one year after it began, and while the increasing trend over 60 years was similar, a limit of 6 was reached 1 year earlier.

In response to the 2 % drying scenario the T:R ratio reached 6 and 8 by year 41, the difference of 0 being 4 and 3 years less than in response to the 1% and 1.5% drying scenarios respectively. By comparison to the 1% and 1.5% drying scenarios, a T:R ratio of 6 marked the exponential increase phase less well, and while the increasing trend over 60 years was similar, a limit of 6 was respectively reached 10 and 9 years earlier.

We took these modelled results as justification for the choice of 6 as the TPC (T:R ratio limit) on ephemerally flooded features, erring on the conservative side. It must also be clearly stated that this TPC is a first estimate, which must be refined and changed if necessary by the SAM process through which it will operate.

Setting limits for the TPC on actively and seasonally flooded features was more difficult because the numbers of terrestrial individuals was often too low to calculate a T:R ratio (we used a cut-off of 10 individuals below which a ratio becomes deceiving). The maximum T:R ratio predicted on seasonally flooded features was 0.7, whereas none was available for actively flooded features. For this reason we decided to use only measured T:R ratios to set as limits, and suggest T:R ratio limits of 0.2 and 1 for active and seasonal features respectively. It must again be emphasised however that these are first estimates that will also need refinement through the SAM process.

Design a monitoring programme for using the Terrestrialisation Model

We designed a monitoring programme for assisting with the use of the Terrestrialisation Model, and laid out and mapped monitoring plots. Data that need to be collected are summarized in Table i.

Table i. Summary of Terrestrialisation monitoring requirements.

Motivation	Data Type	What to Sample	When to Sample	Where to Sample
Essential Data				
Audit TPC and refine model	Probability of occurrence	Counts of stage classes for each species	Every 3 years	Designated monitoring plots on features of different flow category
Refine parameter estimation	Survival	Calculate survival from above counts	Every 3 years and after hydrological events	As above
Refine parameter estimation	Size class longevity	Maximum longevity of all adult stage classes and saplings	Every 3 years	Sample marked individuals
Refine parameter estimation	Density	Calculate site density from above counts and convert to density for 5 X 5 m grids	Update every 3 years	
Model input	Hydrology	Discharge (m^3s^{-1})	Daily	Closest gauging station to site or ACRU (Schulze, 1995)
Model input	Rainfall	Total amount (mm)	Daily	Weather station closest to site or ACRU (Schulze, 1995)
Required to run the model for each site	Hydrological states	Define for each site	Once off and after major floods	At each site
Needed to define additional monitoring	Occurrence of hydrological events	Discharge (m^3s^{-1})	Annually	
Useful Data				
Refine parameter estimation	Seed bank longevity	Germinability after seed collection	Annually	Experimental

One of the aims of the monitoring programme is to refine the Terrestrialisation Model and parameter estimation within the SAM framework. The essence of SAM is that management is flexible, and can be adapted as necessary. Another aim of monitoring is to test the TPCs outside of the predictive framework. Through ongoing monitoring, the necessary data will exist to test TPC's under a variety of conditions.

Development of a protocol for Technology Exchange and Adoption

Joint Principles and User Buy-in

Conventionally, technology transfer comprised the development of research products (such as knowledge, data, rules, models, principles) that were largely developed in isolation of potential users of the products, and then marketed to facilitate their acceptance and assimilation (Figure iiiA).

A more effective model of the principles of technology exchange and adoption is one where joint principles are established between developers and users at the initial/planning stage of technology development (Figure iiiB). As technology development proceeds, these joint principles are reaffirmed and others may be developed. This process whereby interactions between developers and users are critical and necessary is likely to result in automatic buy-in of the new technology by end users. The potential also exists that by the end of development, the new technology would have become part of the user culture, thereby facilitating

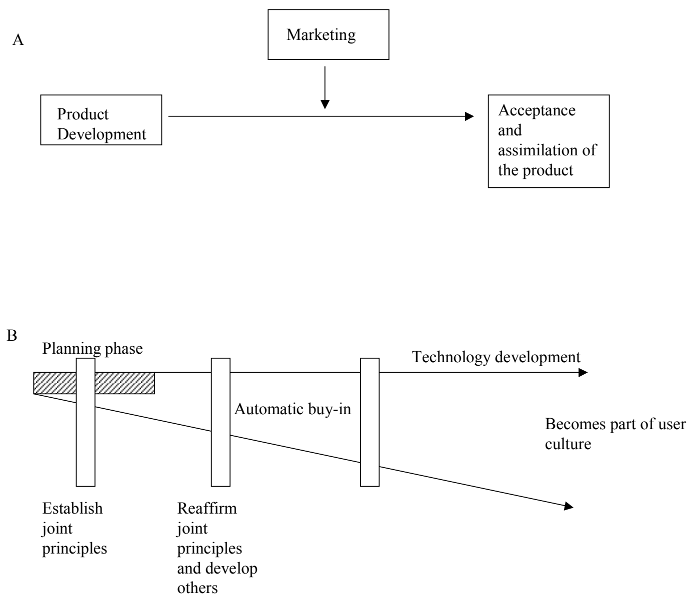

Figure iii. Conceptual models of traditional (A) and emerging (B) principles of technology exchange and adoption.

acceptance and assimilation with ease.

Demand Articulation

Demand articulation is the clear expression of what the users of technology need, with the express intention of guiding developers of technology to meet those needs. Demand articulation may range from a situation where potential users of technology explicitly outline their technological requirements, to a situation where developers of technology inform potential users of what their technological requirements are, and what possibilities exist to meet those. The latter situation is not as foolish as it sounds. The management of ecosystems is all too often impaired by a lack of even a basic understanding of how those systems function or respond to perturbations. Managers do not therefore have knowledge of what their needs are, and research is best employed to elucidate possibilities.

Demand articulation creates a context into which the products of technological advancement can slot. A good example of this is the Objectives Hierarchy that has been set by Kruger National Park and their associates. As its name implies, the objectives hierarchy begins with a broad vision-type statement, which is then decomposed into levels of increasingly detailed management objectives in a hierarchical fashion (Rogers and Bestbier, 1997). At the broadest scale, statements focus more on societal interest, but as statements become more detailed, more emphasis is placed on scientific rigour. The advantages of setting up an objectives hierarchy at the institutional level are numerous (see Rogers and Bestbier, 1997 for these), but we draw your attention to two.

The first advantage is connectivity. Because the hierarchy unfolds with increasing scientific and decreasing societal detail, science and public values are easily linked. This means that scientific methods and products lower down in the hierarchy can easily be related to public values further up in the hierarchy. This not only gives purpose and direction to scientific efforts, but also justifies them in the public eye. This is important for technology exchange and adoption (TEA) because violation or ignorance of societal values is sure to hinder the ultimate success of new technology.

Of course management also fits into the hierarchy. Statements of public interest are transformed into broad management objectives that are then decomposed into more specific management objectives. The more specific objectives become the more scientific they are. This important link between management and science is the 'make or break' of TEA. This is the second advantage we draw attention to. The formalization of an objectives hierarchy creates a forum in which managers and researchers not only interact, but more importantly, articulate demands. Setting up the objectives hierarchy facilitates the establishment of joint principles between prospective developers and users of technological products, and sets the scene for user buy-in and assimilation to become more automatic.

Strategic Adaptive Management

Setting objectives, be they hierarchical or otherwise, is just one way of establishing joint principles, facilitating user buy-in and creating context for technological products. The subsequent arena in which TEA must play is also critical for its success. Bear in mind, both scientists and managers have been known to be wrong. A strategic approach that is also adaptive is therefore most likely to succeed in the exchange and adoption of technological products.

Strategic Adaptive Management (SAM) is recognised as an effective means of managing natural ecosystems (Rogers and Biggs, 1999), albeit with expected problems (Walters, 1997). SAM provides a framework that enhances the exchange and adoption of new technologies because 1) its strategic thrust calls for the setting of clear, achievable and operational management goals that create context for new product development and reception, and 2) its adaptive nature means that new products are less likely to become redundant as they are constantly and iteratively refined within the process of adaptation.

Once again, the KNP provides a good example of SAM facilitation of TEA (Figure iv). A Decision Support System (DSS) consists of research and a predictive and operational framework. First, agents of change and indicators of those agents are identified within the ecosystem of concern. Management objectives in the form of TPCs are then set using this information. Both modelling and monitoring are set in place to assess the achievement of management goals. This is strategic.

If TPCs are exceeded, they become subject to change, or the technologies used for their assessment may need refinement. This can occur via assessment in the predictive framework, which feeds back into research where tools and/or goals are scrutinized for improvement, or where changes in the ecosystem comply with exceedence of thresholds that are within broader values in the objectives hierarchy. This is adaptive.

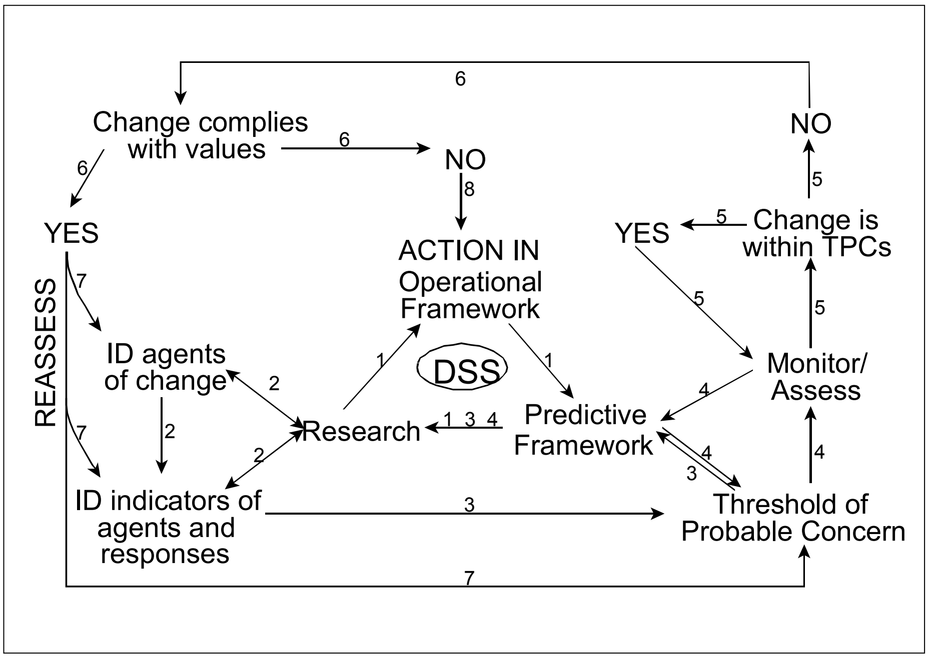

Figure iv. The iterative process of Strategic Adaptive Management used in the Kruger National Park (after Rogers and Biggs, 1999).

The SAM framework affords flexibility for the transfer, exchange and adoption processes, and encourages the evolution of technological products that will serve end users much longer and more efficiently.

Role Overlap and the Importance of People

The importance of interaction between developers and users of technology for effective exchange and adoption has already been alluded to, but cannot be overemphasised. Clearly, for TEA to be effective, teamwork is required.

It is usual for the people at any given organization or institute to relate to one another, or be arranged in the traditional hierarchical fashion (Figure vA). In situations where TEA is envisioned, one would usually expect the interaction of at least two such organizations (Figure vB). A case in point would be scientific services at KNP interacting with research groups such as CWE. The nature of the people within these organizations, as well as the nature of the interactions they cause, has direct influence on the success of TEA. Interactions could be a minimal client-service provider-type interaction (Figure vB), or as in the case of KNP and research groups, interactions could be within the framework of SAM (Figure vC). As we have discussed, there are advantages to employing a SAM framework, but if everyone in respective organizations were to 'just do their jobs', would TEA be successful?

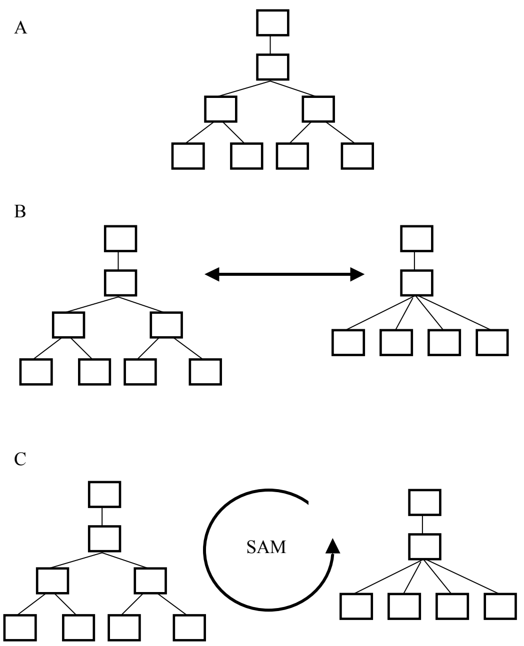

Figure v. A schematic of the traditional arrangement of people at an organisation (A). Interactions between similarly arranged organisations can be minimal and simple (B) or more structured and complex such as within the framework of SAM (C).

We have already stated that both researchers and managers, in the traditional sense, have been stretched in their capabilities to facilitate and promote TEA, as they are required to consider the basic principles of one another's fields of discipline. It is our experience that this form of role overlap has been instrumental in the facilitation of TEA. But what really is role overlap and how much of it is needed for successful TEA?

Role overlap is possibly defined in many ways. We outline two facets of role overlap and suggest that these are crucial to effective TEA. Agreeably, for the conservation or sustainability of natural ecosystems, decision making, knowledge management and operations (consisting of research, monitoring and management) are required. These roles are schematically represented as points in a triangle, with respective arms of the triangle representing conduction or completion of the role (Figure viA). Admittedly, each of these roles can function in isolation, but TEA is likely to then be unsuccessful.

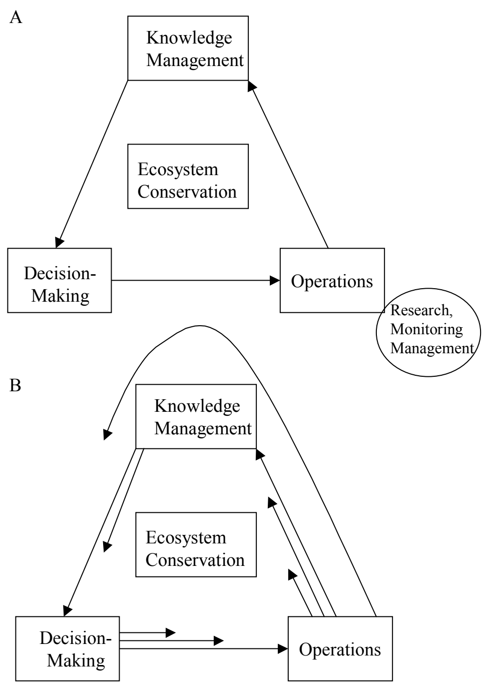

Figure vi. Schematic of the roles necessary for ecosystem conservation operating in isolation (A) and with interaction and role overlap (B).

In a usual ecosystem conservation setting, teams of people will conduct each of these roles. In outlining Figure viA, it was assumed that each role was conducted sufficiently effectively by each team. The overall capability to perform each role however, will be limited by capacity. People with restricted capacity will not generally engage in role overlap (represented by the short arrows of the triangle in Figure viB). Some people are sufficiently capable (complete arrows in the triangle), but also do not engage in role overlap, while few people take an active interest in other roles and engage them to some degree (arrows that round points of the triangle). These, for example, are managers or researchers that also engage knowledge management and/or decision-making.

Another form of role overlap that we suggest is beneficial to effective TEA is experience of, or background to other roles or disciplines. TEA is less likely to succeed when interacting teams have no experience or background of one another’s roles. This is schematically represented by two hierarchical organizations conducting different roles, for example research and management, with no role overlap along a theoretical-practical gradient, which in this case is a traditional measure of the differences between these roles (Figure viiA).

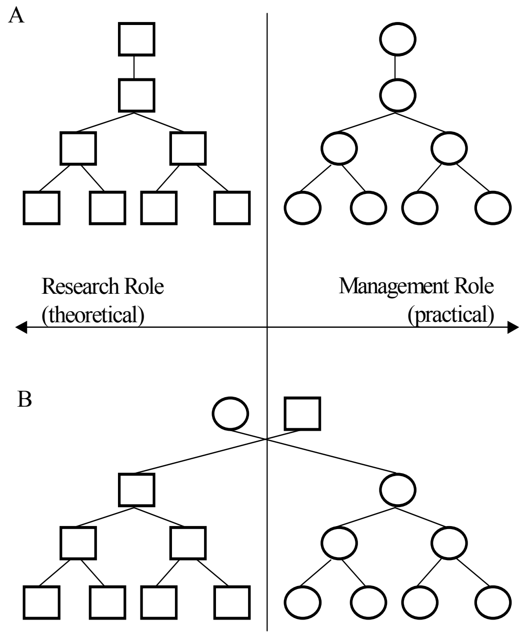

Figure vii. Schematic of hierarchical organizations with different roles where there is no role overlap (A), and where role overlap exists (B).

A more effective way to encourage TEA would be a situation where one or more of the team members representing each role were to, at the very least, express an active interest in other roles, but preferably, to have had experience in performing other roles (Figure viiB). Managers who, for example, have come from a scientific background, or who have scientists in their team, would fit this description.

Protocol

In attempting to set up a protocol to guide and promote TEA, we have focussed on thrusts and attitudes that are likely to facilitate effective TEA. These thrusts and attitudes are properties of the people that engage TEA and will be dependent on the environment in which they occur.

We have defined three environments (Figure viii). The internal environments of 1) developers, 2) adopters, and 3) a multi-level interactive environment in which TEA takes place. The following thrusts and attitudes should characterise the Internal Developer Environment,

1. Development should begin with problem articulation
2. Development should be objective driven
3. Developers should produce high quality, relevant products that are designed to be flexible and refined
4. Scientific rigour should be pursued

whereas the Internal Adopter Environment should be characterised by the following thrusts and attitudes:

1. Adopters should engage demand articulation
2. Adopters should cultivate an attitude of buy-in within themselves and their organization
3. Adopters should attempt to actively participate in the development of new technologies, even if all that is possible is a keen interest

Multi-level interactions between developer and adopter organizations create the environment in which TEA takes place. These interactions should be characterised by thrusts and attitudes that:

1. Define joint principles at both planning and development phases
2. Embrace frameworks that facilitate TEA, such as SAM
3. Encourage SAM frameworks
4. Engage role overlap where possible
5. Pursue networking between people and organizations where multi-level interactions are frequent and engage feedback mechanisms
6. Recognise and utilise key personalities

RECOMMENDATIONS FOR FUTURE RESEARCH AND TECHNOLOGY EXCHANGE AND ADOPTION

In the following section, we outline lessons that we have learnt with respect to TEA, during the course of developing, exchanging and adopting both the *Breonadia* and Terrestrialisation Models and their associated TPCs, as well as recommendations for more effective TEA:

1. For potential users of new technologies to be aware, and even approve of the development of new technological products, is not necessarily enough to ensure effective TEA.
2. Users and developers of new technologies should be prepared, and expect to define joint principles at both the planning and development phases.
3. Problem and/or goal definition should precede technological advancement, and should not be divorced from institutional/organizational structure, function and peculiarities.
4. Technological products should be the result of team effort. This means that prospective users should not only be aware of planning and progress (attending steering committee meetings for example), but should be incorporated in the actual development at relevant levels.
5. Technological products should be developed with flexibility to change or be refined with use, and should embrace the framework of SAM.
6. Prospective users of new technologies should prepare themselves (at least at the personal scale, but preferably at the corporate scale) to be strategic and adaptive in their roles.
7. Utilization of and interaction with key personalities should be pursued when engaging TEA.
8. Prospective users of new technologies should make an effort to promote buy-in and use. This is a recognised recommendation as outlined by the following quote from minutes of a workshop held on July 18, 2001 to discuss the research and technology transfer process:

   "3.1.2 **Dr Mitchell** suggested that the users should act as a third signatory to the contract to ensure that technology transfer would happen. **Dr Biggs** went further to say that they should not only sign it, but the level of handover responsibility should be specified (e.g., for a modelling based project would it constitute a report, scenarios, an installed modelling system, or a running software product with training given). **Dr Mkhize** noted that these agreements would have to be tailor-made for each project and could not be a standard/form document."

9. Some members of each team should, at least in principle, be prepared to engage role overlap.
10. Corporate structures that promote SAM frameworks should be encouraged, and developers and users alike should prepare themselves to embrace these frameworks.
11. Multilevel interactions between organizations are likely to result in more effective TEA than single level interactions (Figure ix). A technological product (P) that is developed by one organization and adopted by another is less likely to succeed if only the developer and user interact (Figure ixA). Multilevel interaction is required, not only within organizations, but between them (Figure ixB), and these interactions should centre around the technology being developed and adopted as well as the supportive environment in which TEA will take place.

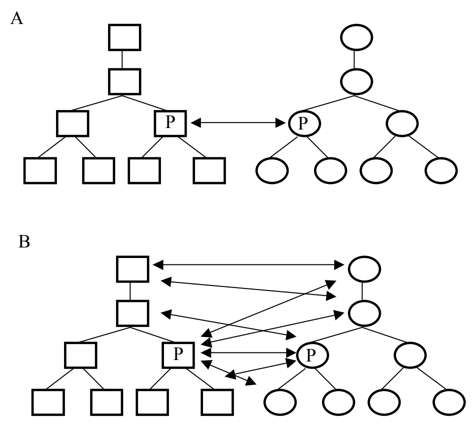

Figure ix. Schematic illustrating single- (A) and multi-level (B) interactions between organisations engaged in TEA for a specific product (P).

CONCLUSION

We hypothesize that the processes or agents of change underlying an increase in terrestrial species in the riparian zone are a reduction in flooding frequency for a given stage, reduced water availability from the water table, and increased sediment accumulation on bars.

Managers within the KNP use thresholds of probable concern (TPC) to alert them to unacceptable change occurring in ecosystems. The TPC for terrestrialisation of the macro-channel floor is expressed as the ratio of the abundance of key terrestrial plant species to the abundance of an equal number of key riparian plant species along a gradient of flow frequency and availability of water from the water table.

Management of the KNP is based on strategic adaptive management (SAM), of which research is an important component. A decision support system (DSS) provides a technological interface between management and research. KNP managers have described the desired state of the rivers, and use operational goals to ensure that this state is achieved.
Monitoring is a critical aspect of management, as it allows goals to be audited to ensure that ecosystem change is towards the desired state.

We developed two rule-based models (the *Breonadia* and the Terrestrialisation Models) which can be used in predictive management. The *Breonadia* Model has value as a management tool because it:

- Predicts the population response of *Breonadia salicina* to rainfall, hydrology and geomorphology.
- Audits the TPC for the loss of bedrock influence, of which *B. salicina* is an indicator.
- Guides decision makers with a formal protocol for using TPC audits in decision making.
- Can be used to generate and evaluate scenarios of the consequences of change in catchment characteristics and processes.
- Enables users to easily interpret results by presenting input and rule summaries with outputs.
- Can easily incorporate monitored data to improve parameter estimates.
- Utilizes a user-friendly interface and graphical presentation of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.
- Together with the Help manual, can be downloaded from the Internet.

The Terrestrialisation Model has value as a management tool because it:

- Predicts encroachment into the riparian zone by terrestrial individuals.
- Audits the Terrestrialisation TPC.
- Can be used to generate and evaluate scenarios of the consequences of change in catchment characteristics and processes.
- Enables users to easily interpret results by presenting input and rule summaries with outputs.
- Can easily incorporate monitored data to improve parameter estimates.
- Utilizes a user-friendly interface and graphical presentation of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.
- Together with Help facilities, can be downloaded from the Internet.

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LIST OF ACRONYMS

ACRU	Agricultural Catchments Research Unit
DSS	Decision Support System
KNP	Kruger National Park
KNPRRP	Kruger National Park Rivers Research Programme
RBM	Rule Based Model
SAM	Strategic Adaptive Management
TEA	Technology Exchange and Adoption
TPC	Threshold of Probable Concern
T:R Ratio	Ratio of Terrestrial to Riparian Individuals

HYDROLOGICAL DEFINITONS

No flow: There is no flow in the river, and only standing water in the pools

Extreme low flows: Minimal amount of water needed for flow in river

Base flows: Activation* of active features, but no inundation of active bars

Intermediate flows: Inundation of active features and activation* of seasonal features

High flows: Inundation of about 50% of seasonal features and activation* of remaining seasonal features

Very small floods: Inundation of seasonal features and activation* of ephemeral features

Small floods: Inundation of about 30% of ephemeral features

Large floods: Inundation of about 50% of ephemeral features

Catastrophic floods: Inundation of about 100% of ephemeral features (bank full flow)

*: activation is defined as the amount of water needed to just reach the feature and moisten it, but not inundate it.

CHAPTER 1

INTRODUCTION

1.1 MOTIVATION AND RATIONALE

In South Africa, flow regimes of rivers that traverse the Kruger National Park (KNP) are expected to change in response to catchment developments outside and upstream of conservation areas. These developments will have ongoing consequences for heterogeneity within riparian zones. One of these consequences may be the encroachment of terrestrial species into the riparian zone, which may be detrimental to riparian species and could reduce both heterogeneity and diversity. However, there have been few studies on the flow requirements of South African river systems (Rogers, 1995), and our ability to predict the effect of altering the flow regime is thus limited. We hypothesize that riparian vegetation structure and composition are altered by changes in flow and geomorphology, and aim to increase our understanding of the effects of these changes.

Changes in land use have affected river catchments in most countries (Pettit and Froend, 2001). However, riparian zones in semiarid areas are particularly sensitive to water level changes, and declines in groundwater levels can result in reduced abundance of riparian vegetation (Stromberg *et al.*, 1996). Development (forestry and agriculture) in the Sabie River catchment has resulted in an altered flow regime, and has caused much concern regarding the geomorphological and ecological functioning of the river (van Coller and Rogers, 1996). The Kruger National Park occurs downstream of developments, and as the majority of the Sabie River's water comes from the upper catchment, it is directly affected (van Coller and Rogers, 1996). The question of importance that we address is whether future river regulation, or natural change will favour encroachment by terrestrial species in the riparian zone, and whether these compositional changes will be within the KNP management objectives.

Riparian zones regulate aquatic-terrestrial linkages, protect and maintain the instream river ecosystem, and provide important and specialized habitat which increases diversity (Gregory *et al.*, 1991; Franklin, 1992; Naiman *et al.*, 1993; Naiman and Décamps, 1997; Pettit and Froend, 2001). They are one of the most dynamic and complex ecosystems, and exhibit a high degree of structural and compositional diversity (Gregory *et al.*, 1991; Naiman and Décamps, 1997). Riparian zones are particularly sensitive ecosystems, especially with regards to the edge effect between aquatic and upland habitats, and environmental change (Gregory *et al.*, 1991; Tabacchi, 1995; Naiman and Décamps, 1997).

Terrestrial systems affect riparian ecosystems (Elmore, 1992), and increased knowledge of the impact of terrestrial species occurring within the riparian zone is needed. In addition, geomorphic and disturbance processes from both the upland and the river affect the riparian zone, influencing the spatial pattern of riparian vegetation (Gregory *et al.*, 1991). Hydrologic and geomorphic processes and interactions critically influence the structure, dynamics, and composition of riparian vegetation

(Johnson, 1994; van Coller and Rogers, 1996; Naiman and Décamps, 1997; Tabacchi *et al.*, 1998), and managers need a firm understanding of these processes.

Riparian systems are renowned for their sensitivity to invasion by exotic species (Tabacchi, 1995). Terrestrial species encroaching and persisting within the riparian zone may, however, constitute a similar problem. Under favourable conditions, encroachment may be to such an extent that diversity and heterogeneity are reduced. This can have serious consequences in rivers such as the Sabie, which is one of the least impacted in South Africa (James *et al.*, 1996; Heritage and Moon, 2000), and flows through major conservation areas including the Kruger National Park (KNP). However, the Sabie River occurs in a semi-arid and developing setting, and future flow regimes are likely to change. There is thus a need to predict the response of both riparian and terrestrial species occurring in the riparian zone to these changes in flow regime.

1.2 MANAGEMENT STRATEGY IN THE KRUGER NATIONAL PARK

Managers of the KNP implement strategic adaptive management (SAM) to meet their goals. Research is a critical component of SAM, and a decision support system (DSS) provides a technological interface between management and research (Rogers and Bestbier, 1997). Using such a DSS, a description of the desired state of the rivers in the KNP was set, and was then translated into operational goals that were also auditable in terms of achieving the desired state (Rogers and Bestbier, 1997). In setting conservation goals, attention was focused on establishing functional Thresholds of Probable Concern (TPCs), which represent limits of acceptable change in ecosystem structure and function. An effective monitoring programme was established to help audit the achievement of these TPCs. A fundamental component of the management process is a predictive modelling framework that enables prediction of the consequences of management actions for the achievement of conservation goals (TPCs) (Rogers and Bestbier, 1997; Rogers and Biggs, 1999). It is within the modelling framework that predictive tools such as rule based models are utilized. Models become effective management tools when they incorporate management goals directly.

The Kruger Park Rivers Research Programme made major strides in developing innovative protocols for integrating research, predictive modelling, and goal auditing to enable ground breaking strategic adaptive management (SAM) of the environment (Rogers and Bestbier, 1997; Rogers and Biggs, 1999). The concepts behind the protocols have been enthusiastically embraced by conservation and environmental management agencies, but much needs to be done to operationalize them. Central to this operationalization is the development and transfer of appropriate technology for the processes of management and auditing of goal attainment.

A project to develop a rule based model (RBM) for the management of riparian systems (MacKenzie *et al*, 1999) has developed a model referred to as the *Breonadia* Model. This model services the TPC set as a management goal relating to the loss of bedrock influence on the Sabie River. The *Breonadia* Model can be used by managers to predict whether thresholds of probable concern (TPCs) for riparian vegetation are likely to be exceeded under different management scenarios. The project also conceptualized other models that are needed to audit other KNP river management goals and developed unique expertise in rule based modeling, which was suggested as the most appropriate route to take to predictive science and management. Above all, the project generated an understanding of the time and resources needed to develop and implement SAM orientated models, and we are now in a better position to plan and implement modelling projects and predictive capacity in river management.

1.3 CONCEPTUALIZATION OF THE TPC FOR TERRESTRIALISATION OF THE RIPARIAN ZONE

Terrestrial species which occur in the savanna may also be found within the riparian zone, but display a gradient of decreasing abundance with reduced distance from the active channel (van Coller, 1993). However, a progressive increase in the abundance of terrestrial individuals relative to the abundance of riparian individuals within the riparian zone, which we refer to as terrestrialisation, has the potential to reduce diversity and heterogeneity. The TPC for terrestrialisation of the macro-channel floor is expressed as the ratio of the abundance of key terrestrial plant species to the abundance of an equal number of key riparian plant species along a gradient of flow frequency and availability of water from the water table. The TPC incorporates natural flux within the system, and alerts managers to a potential problem if the limit is exceeded.

The natural flow regime of the Sabie River (winter low flows and summer high flows) contains both regular seasonal disturbance, and irregular seasonal disturbance, with peaks occurring in summer. Riparian vegetation successfully establishes and persists under this flow regime, whereas terrestrial vegetation does not experience flooding in its optimal environment. We therefore hypothesize that the processes or agents of change underlying an increase in terrestrial species in the riparian zone are a reduction in flooding frequency for a given stage, reduced water availability from the water table, and increased sediment accumulation on bars.

1.4 AIMS AND OBJECTIVES

The overall aim of the project was to engage research, prediction, technology transfer and monitoring through rule based modelling, to enable effective management of riparian system response to changes in flow regime and geomorphology.

To achieve this aim, the following specific objectives were pursued:

1. Transferal and implementation of the existing *Breonadia* Model (MacKenzie *et al.*, 1999) to Kruger National Park management. This model services the management goal [Threshold of Probable Concern (TPC)] to reduce the loss of bedrock influence on the Sabie River.
2. Implementation of a structured monitoring programme to provide data for using the Breonadia Model to test the TPC set by Kruger National Park (KNP) management.
3. a) Conversion of existing conceptual models to address another TPC, that of terrestrialisation of the riparian zone, into an operational RBM.

   b) Transferal of the model to KNP management.

   c) Design and implementation of a monitoring programme for testing the model.

4. a) Identification of problems associated with the transfer of this predictive technology into the SAM process being instituted by KNP management
   b) Use of the understanding gained from the project to develop a protocol of technology transfer for use in strategic river management by other river managers and catchment user groups.

1.5 RESEARCH PRODUCTS AND TARGET GROUPS

Products: Two separate computer driven rule based models, manuals for each model, a structured monitoring programme for each model, guidelines for use of the models in auditing the TPC's, and a structured process for technology transfer and predictive modelling in river and environmental management.

Potential application of products for target groups

1. Conservation management of riparian systems by conservation and environmental organizations (especially Kruger National Park), forestry and catchment user groups, and provincial departments.
2. Incorporation of riparian requirements into IFR assessments by groups such as DWA&F, KNP, and consultants.
3. River resource use policy formulation by statutory bodies.

1.6 STUDY AREA

1.6.1 Catchment characteristics

The catchment of the Sabie River spans two countries, as it is situated in the Mpumalanga province in South Africa, and the southern lowland region of Mozambique. It has an area of 7096 km^2, of which 6347 km^2 occur within South Africa (Chunnet and Fourie, 1990) (Figure 1.1). The Sabie River has its origins in the Drakensberg escarpment, at an altitude of 2200m, from where it flows eastwards for 210km to its confluence with the Inkomatie River in Mozambique. The 106km section with which this study is concerned extends from the eastern to the western boundary of the KNP, and occurs in the lowveld zone where the topographical gradient is low. The section of river selected for the present study extends from the western to the eastern border of the Kruger National Park (between 24°58'S, 31°16'E and 25°10'S, 32°01E).

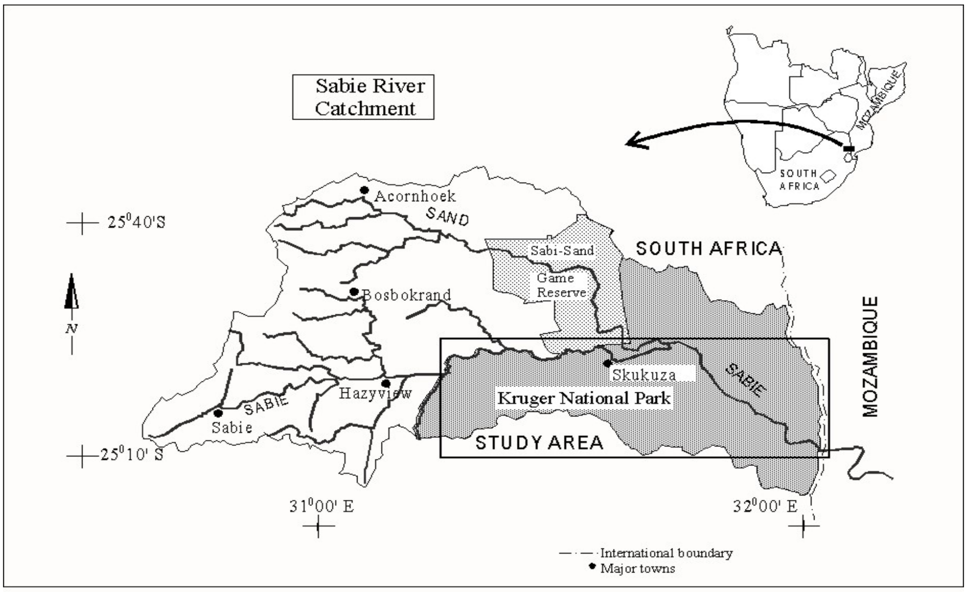

Figure 1.1 Location map showing the Sabie River and its catchment (after MacKenzie *et al.*, 1999).

The human population within the Sabie River catchment is expected to increase from estimates of 338 000 people in 1985 to about 1 266 000 people by the year 2010. In 1985, approximately 80 000 people outside the Sabie catchment boundaries were also dependent on its water, and it is estimated that this number of people will increase to 166 000 by the year 2010 (Chunnet and Fourie, 1990).

1.6.2 Geology and geomorphology

The geology through which the Sabie River flows is diverse and complex and has been described in detail by Cheshire (1994). Geology plays an important role in influencing geomorphology of the river, which has been described in detail by van Niekerk and Heritage (1993) and Heritage *et al.* (1997). The Sabie River within the Lowveld is slightly incised into the Post African II surface forming a macro-channel with steep, stable banks on either side of the more dynamic macro-channel floor.

The Sabie River is a mixed bedrock-alluvial system, displaying characteristics of both bedrock and alluvial influence (van Niekerk and Heritage, 1993; Moon *et al.*, 1997), and therefore has a high diversity of morphological units (van Coller *et al.*, 1997). Four main channel types and various geomorphic units along the section of Sabie River within the KNP were identified by van Niekerk and Heritage (1993). As a result of land degradation upstream of the KNP, sediment loads into the river are likely to increase, and there is the potential for the geomorphological structure to be altered through increased sediment storage. A number of studies have been conducted in the Sabie River catchment to quantify sediment production (Rooseboom *et al.*, 1992; van Niekerk and Heritage, 1994; Wadeson and Rowntree, 1995; Donald *et al.*, 1995).

1.6.3 Climate and hydrology

The region is characterized by a semi-arid to sub-tropical climate with hot summers and warm winters. There is a gradient of decreasing rainfall from west (1800-2000 mm/a) to east (450-650 mm/a) with the majority of the precipitation in the catchment occurring up on the escarpment outside the KNP. Rainfall occurs mostly during the summer months (October to February). Inside the KNP, mean annual evaporation is higher than the mean annual precipitation, with evaporation being lower in the west (1400 mm/a) than the east (1700 mm/a) (Heritage *et al.*, 1997).

Flow in the Sabie River is perennial, although extremely variable, and extreme discharges are not uncommon (Chiew and McMahon, 1995). Flooding is closely associated with summer rainfall in the form of thunderstorms, and low flows occur during winter and periods of drought. Hydrological records exist at three sites along the river, dating as far back as 1959 at Perry's Farm, 1987 at Lower Sabie, and 1990 at Skukuza (Heritage *et al.*, 1997). Simulated flow records from rainfall runoff have also been calculated for as far back as 1932. Recently the Sabie River experienced a severe drought (1992), a flood of approximately 1 in 50 year return period (1996), and a flood of approximately 1 in 100 year return period (2000), providing an opportunity to observe event impacts on riparian vegetation and geomorphological change. The flow regime in the Sabie River within the KNP has been altered over the years by abstraction of water for various land use practices (Chunnet and Fourie, 1990), and the construction of the Inyaka dam on the Marite River (a major tributary of the Sabie) has further altered the natural flow regime.

Catchment developments along the Sabie related to changing land use and water abstraction result in increased sediment loads and reduced capacity to transport sediments through the river system. This situation has the potential to change the geomorphological structure of the Sabie River. The nature of this change will result in the loss of exposed bedrock, which has been shown to be an important influence on biodiversity (van Coller, 1993; Heritage *et al.*, 1997; Mackenzie, unpublished data). Certain riparian plant species, for example, rely on the presence of exposed bedrock to establish and persist. In addition, patterns of riparian plant distribution are affected by the presence of sediment. Managers of the Sabie River therefore need to understand the effects of bedrock and sediment distribution on vegetation, in order to fully meet their objectives and goals.

1.6.4 Vegetation

Vegetation along the Sabie River within the KNP has been described by Acocks (1988), Bredenkamp and van Rooyen (1991), van Rooyen and Bredenkamp (1996a; 1996b) and van Coller *et al.* (1997). The interaction between hydrology and fluvial geomorphology is critical to understanding vegetation spatial patterns. Strong environmental gradients (vertical, lateral and longitudinal) 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. Discontinuities in species distribution patterns along these gradients, and on geomorphological features, have been used to define vegetation types (van Coller *et al.*, 1997).

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 identified within the riparian zone by van Coller *et al.* (1997), and named according to the dominant species. These are *Phragmites mauritianus* reed vegetation, *Phyllanthus reticulatus* shrub vegetation, *Combretum erythrophyllum* open deciduous woodland, *B. salicina* closed evergreen woodland, *Diospyros mespiliformis* closed and open woodland, and *Spirostachys africana* open woodland. These vegetation types were shown to be closely associated with geomorphological features, with the latter two occurring on the macro-channel bank, and the former four occurring on the macro-channel floor.

CHAPTER 2

LITERATURE REVIEW

2.1 STRATEGIC ADAPTIVE MANAGEMENT

The management of natural systems has undergone substantial change in recent years. In the past, management attempted to reduce the extremes of ecosystem behaviour by implementing a command-and-control approach, which attempted to increase the predictability and stability of natural systems (Holling and Meffe, 1996; Rogers, and Bestbier, 1997). This approach generally resulted in a reduction in the range of natural variation of systems, a decrease in heterogeneity, and a lowering of ecosystem resilience. Systems became more predictable and profitable, resulting in short-term economic gain, but the vulnerability of the ecosystem was increased (Holling and Meffe, 1996). This type of management is being replaced by flexible, adaptive management (Holling, 1978; Walters, 1986). Adaptive management is "a structured process of "learning by doing" that involves much more than simply better ecological monitoring and response to unexpected management impacts" (Walters, 1997). "Management by experiment" is another way of describing adaptive management, where management actions are treated as potential learning opportunities, and the information obtained is used to improve decision making (Rogers and Biggs, 1999).

An important component of adaptive management is the integration of interdisciplinary experience and scientific information into models, to make predictions of the impacts of alternative policies (Walters, 1997). Modelling has various important functions, which include problem clarification and improved communication between scientists, managers, and other stakeholders; identifying options that are unlikely to be beneficial; and recognizing knowledge gaps in the model (Walters, 1997). Models can therefore be used to investigate a number of different scenarios, from which the most acceptable can be chosen (Walters, 1997).

By investigating a number of scenarios, management is able to be strategic rather than reactive. This is in contrast to the command-and-control type of management, which tends to respond reactively only after unfavourable changes have occurred. In contrast, strategic adaptive management is based on a partnership between science and management that focuses on pragmatic, goal-orientated adaptive management (Rogers, 1998).

There are various types of goals. Institutional goals "define achievable targets for managing institutional structures and processes", whereas conservation goals "define endpoints for ecosystem management and must thus be scientifically rigorous without compromising the value systems embodied in the vision" (Rogers and Biggs, 1999). The endpoints are also referred to as thresholds of probable concern (TPCs) (Rogers and Bestbier, 1997). They represent limits of acceptable change within an ecosystem, and thus act as a warning to managers when the system is moving away from the desired state towards possible unacceptable environmental change. TPCs are essential in monitoring, and form a link between management goals and science

(Rogers and Biggs, 1999). Within the KNP, TPCs have been set to audit goal attainment in strategic management of the Sabie River.

An uncritical approach to science results in problems being badly defined and solutions being accepted without questioning, and without considering how they relate to predefined management goals, resulting in inefficient management (Rogers and Biggs, 1999). In addition, monitoring programmes often assess the state of the system, rather than explicitly monitoring the consequences of management actions. Thus, because it lacks direction, purpose and a defensible scientific base, management often becomes highly reactive (Rogers and Biggs, 1999). Strategic adaptive management has direction and can act strategically to prevent undesirable change occurring.

2.2 MANAGEMENT ORIENTED MODELLING

It is generally accepted that there is a lack of co-ordinated effort to understand and manage riparian corridors in southern Africa (Rogers and Naiman, 1997). There is a need to integrate scientific information with decision making, and this information must be communicated to managers in an understandable form (Naiman, 1996). Projects such as "Modelling abiotic-biotic links in the Sabie River" (Jewitt *et al.*, 1998) and "Rule based modelling for management of riparian systems" (MacKenzie *et al.,* 1999) arose because managers and scientists in the KNP realised that management goals in the KNP were not being met. The models were a means of addressing this problem.

2.2.1 The advantages of using models

In conservation management there is often a gap between science and management because scientists are reluctant to commit themselves to quantifying biological requirements without the existence of sufficient data to support suggested values, and managers need specific answers quickly so that decisions can be made. In these situations, a model would serve two important functions. Firstly, modelling can be powerful in promoting communication between disciplines (Starfield, 1997), and secondly a model ensures better informed decisions and management actions, even without data.

Models have been defined in various ways. They are essentially representations or abstractions of systems or processes (Starfield and Bleloch, 1991). We develop and build models because they help us to define our problems, organise our thoughts, understand our data, audit goals, calculate solutions, and make predictions. There are a variety of models that are not mutually exclusive (a few examples are deterministic, stochastic, descriptive, mechanistic, dynamic, non-dynamic, computer, matrix, qualitative, quantitative, rule based, frame based, and word models). Modelling is a tool for synthesis and adaptive policy design (Walters and Korman, 1999).

Models of biological interactions are generally dynamic, deterministic models (Brown and Rothery, 1994). However, these models require data to support predictions or calculations. An advantage of rule based modelling (Starfield and Bleloch, 1991) is that it does not emphasize complex mathematics and enables the development of dynamic, deterministic models in data poor environments. Qualitative rule based models (Starfield, 1990) are particularly useful in data poor situations because they are based on heuristic logic (Davis *et al.*, 1986), provide a format for the structuring of knowledge using logical inference (Nicolson and James, 1995), and can indicate which types of data should be collected to improve confidence in predictions.

Modelling based on both hydrologic data and vegetation structure has essential management implications for riparian ecosystems (Stromberg *et al.*, 1993a). These models can be used to make predictions and to improve the understanding of the functioning of the system (Stromberg *et al.*, 1993a). Increasingly, ecosystem management involves an actively adaptive, experimental process, and modelling is essential to enable identification of key uncertainties (Walters and Korman, 1999). Models can be used to provide alternative scenarios to assist decision-making, and provide a holistic perspective (Naiman, 1996).

The *Breonadia* model is an example of a rule-based model that was effectively developed in a data poor environment, and which is being used successfully as a predictive tool for the management of the Sabie River (MacKenzie *et al.*, 1999). Managers are able to consider different scenarios before deciding on the most efficient management actions, and it is used to guide decision makers with a formal protocol for using TPC audits in decision-making.

2.2.2 Context for pragmatic modelling

In conservation management, there is often disparity between science and management because scientists are reluctant to commit themselves to quantifying biological requirements without sufficient data to support suggested values, and managers need specific answers quickly so that decisions can be made. In these situations, models promote communication between disciplines (Starfield, 1997), and can facilitate more informed decisions and management actions (even without data).

Misconceptions about developing models are rooted in the assumption that models accurately describe reality, and can therefore be considered as representing the truth (Starfield, 1997). The pragmatic approach to modelling does not make this assumption, and defines a model rather as a hypothesis, an experiment or a problem-solving tool (Starfield, 1997). Pragmatic models are therefore "purposeful representations" (Starfield *et al.*, 1990) rather than truthful representations.

Brown and Rothery (1994) discuss in detail the mathematics of interaction, indicating that models of biological interaction will generally be dynamic, deterministic models. Their models are mathematical in nature, however, and require data to support predictions or calculations. Rule-based modelling is an approach that de-emphasises the necessity for complex mathematics (although not exclusively), and enables the development of dynamic, deterministic models in situations where data are sparse or absent (Starfield and Bleloch, 1991). Qualitative rule-based models (Starfield, 1990) are particularly useful in data poor situations because they are based on heuristic logic (Davis *et al.*, 1986), provide a format for the structuring of knowledge using logical inference (Nicolson and James, 1995), and can indicate which types of data are best to collect to improve confidence in predictions.

Most scientists need to adjust their mind-set to accept that a model is a purposeful tool rather than a representation of reality, and it requires an act of faith to build models on the basis of insufficient data or poorly substantiated assumptions. We adopted a pragmatic modelling approach, which proposes a suite of small single purpose models rather than large multi-purpose models, and requires that managers have specific goals clearly stated prior to commencement of model development (Starfield, 1997). It was appropriate therefore, at the commencement of model development, that managers of KNP, together with scientists, were in the process of defining a desired state for the KNP through the development of an objectives hierarchy for management of the Park (Braack, 1997).

The hierarchy begins at the broadest level with the overall vision for management. This broad vision requires that managers "maintain biodiversity (*sensu* Noss, 1990) in all its natural facets and fluxes and to provide human benefits in keeping with the National Park, in a manner which detracts as little as possible from the wilderness qualities of the KNP" (Braack, 1997). This vision is then progressively broken down into a series of objectives of increasing focus, rigour and achievability (Rogers and Bestbier, 1997; Rogers and Biggs, 1999). The lower level goals are scientifically based, spatially and temporally bounded targets of ecosystem condition. These targets, called Thresholds of Probable Concern (TPCs), act as amber lights to warn managers of possible unacceptable environmental change. It is appropriate to elaborate on, and provide context for the concept and use of TPCs, as they are central to the guidance of the pragmatic approach to modelling adopted in this study because TPCs are in essence management objectives.

2.2.3 The development and use of TPCs

TPCs define the upper and lower levels of change in selected biotic and abiotic variables which act as indicators of acceptability of ecosystem condition (Rogers and

Biggs, 1999). Research identifies the main agents of change in river characteristics and the indicators of these agents (Rogers and Biggs, 1999; Figure 2.1). Upper and lower levels of these indicators are defined spatially and temporally by managers and scientists to reflect levels of concern of ecosystem change. In so doing, TPCs define a range of flux of acceptable change, and thus account for variability and heterogeneity exhibited by the system. It must be realised that these TPCs represent an inductive approach to strategic management, and are therefore hypotheses about limits of acceptable change in the ecosystem. TPCs are therefore not fixed but are subject to scrutiny and need to be strategically modified if they are found to be invalid or inappropriate.

Monitoring provides a means for evaluating the validity and appropriateness of TPCs, through information transfer regarding change of the indicators, to the predictive framework, which ideally is in the form of a model (Rogers and Biggs, 1999; Figure 2.1). As long as change falls within the upper and lower defined levels of the TPC, then monitoring continues. If, however, through monitoring or predictive modelling, predefined upper or lower levels of the TPC are shown or predicted to have been exceeded, then assessment of the cause, degree and nature of the change relative to the values encompassed in the higher level objectives is necessary. Should the change comply with these values, the information is transferred to researchers to test the validity of the TPC. If the change does not comply with these values, then action is taken within the operational framework to address the causes of change. TPCs are thus a concept that can be used by managers to assess change in the ecosystem, and alert them to take appropriate action. For this reason, we have adopted the TPC philosophy and use it explicitly in our pragmatic approach to guide the development of models.

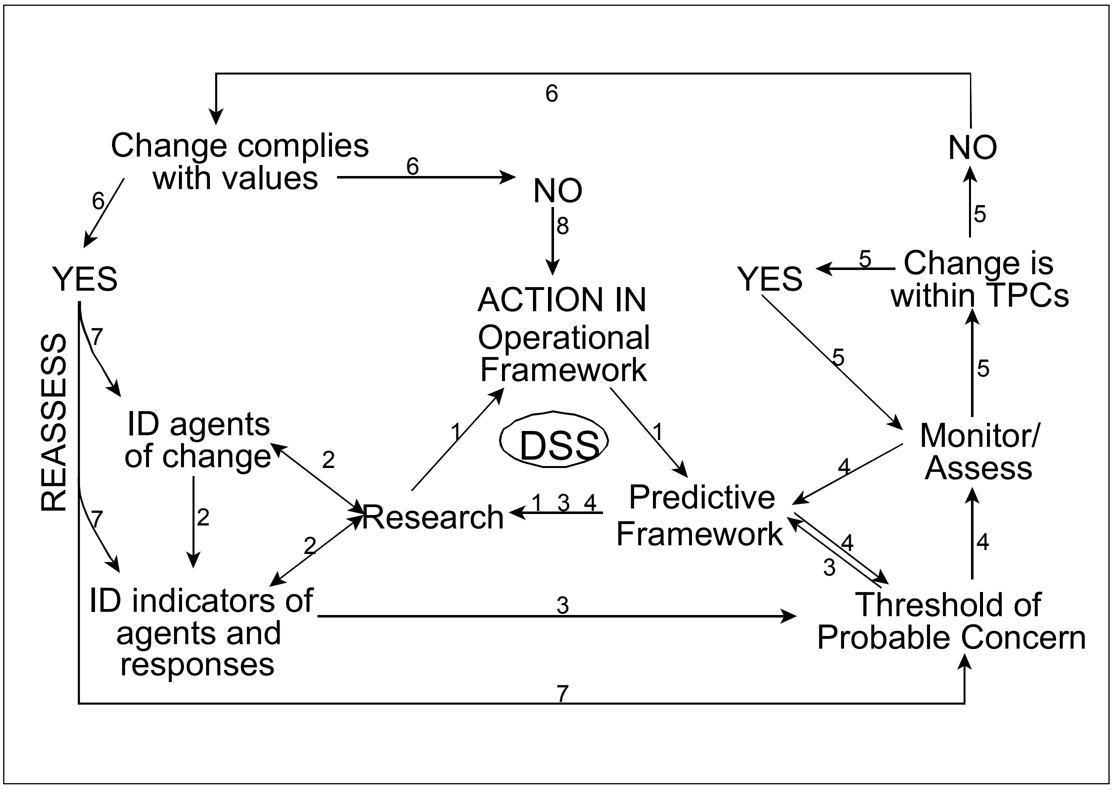

Figure 2.1 The iterative process whereby Research, Prediction and Operations interact with Monitoring of System Response to develop, test and audit Thresholds of Probable Concern (TPCs). The numbers on the arrows define the sequence in which steps are taken. DSS refers to Decision Support System (after Rogers and Biggs 1999).

2.2.4 The use of TPCs to guide model development

The construction of conceptual models that identify different model components and the relationships between components is critical for model development. A first step in our case, is to construct a conceptual model that embodies all possible components involved in riverine and vegetation dynamics, representing what one would expect to find in reality. We call this conceptual model the ‘entire system model’ (Figure 2.2). The conventional route to modelling would be to develop a model that includes as many of the components of reality or the 'entire system model' as possible within the modelling framework. This approach promotes a large multipurpose model that reflects as much of the system dynamics as possible.

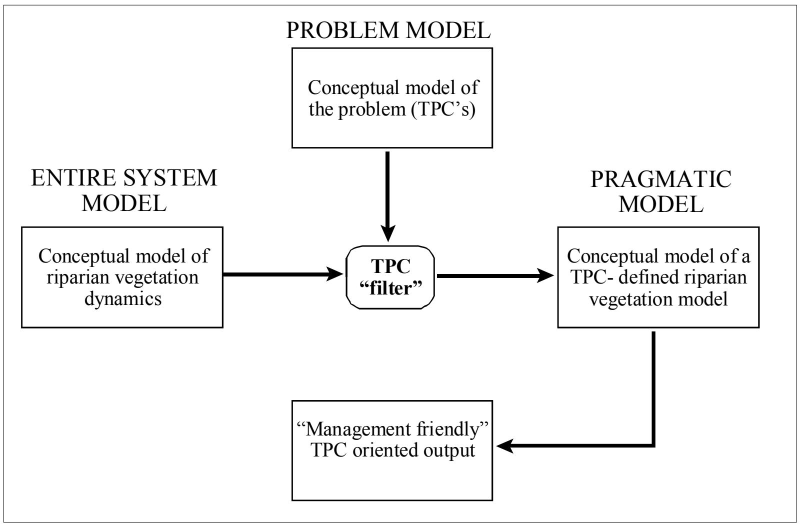

Figure 2.2 The use of TPCs in guiding model development.

A pragmatic approach to modelling calls for the explicit inclusion of objectives prior to and during model development, however. We include objectives as the 'problem model' (Figure 2.2). The problem model includes problem/s relevant to management, which in this case are defined in terms of TPCs. The TPCs which form the basis of the problem model, constrain the conversion of the entire system model to what we have termed the 'pragmatic model'. TPCs act to "filter" academic complexity of the entire system model. In so doing, only the essential components of the entire system model that are relevant to management are included in the pragmatic model. This is best illustrated by an example (Figure 2.3): The entire system model comprises a detailed conceptualization of current understanding of riparian vegetation dynamics, and following the use of the 'TPC filter', only the essential components remain to form the pragmatic model. Management has thus directly guided model development by defining problems (TPCs), which are explicit in the filtering process from the entire system model to the pragmatic model. The result is a suite of smaller problem specific models that produce a predictive output useable by managers within their operational framework.

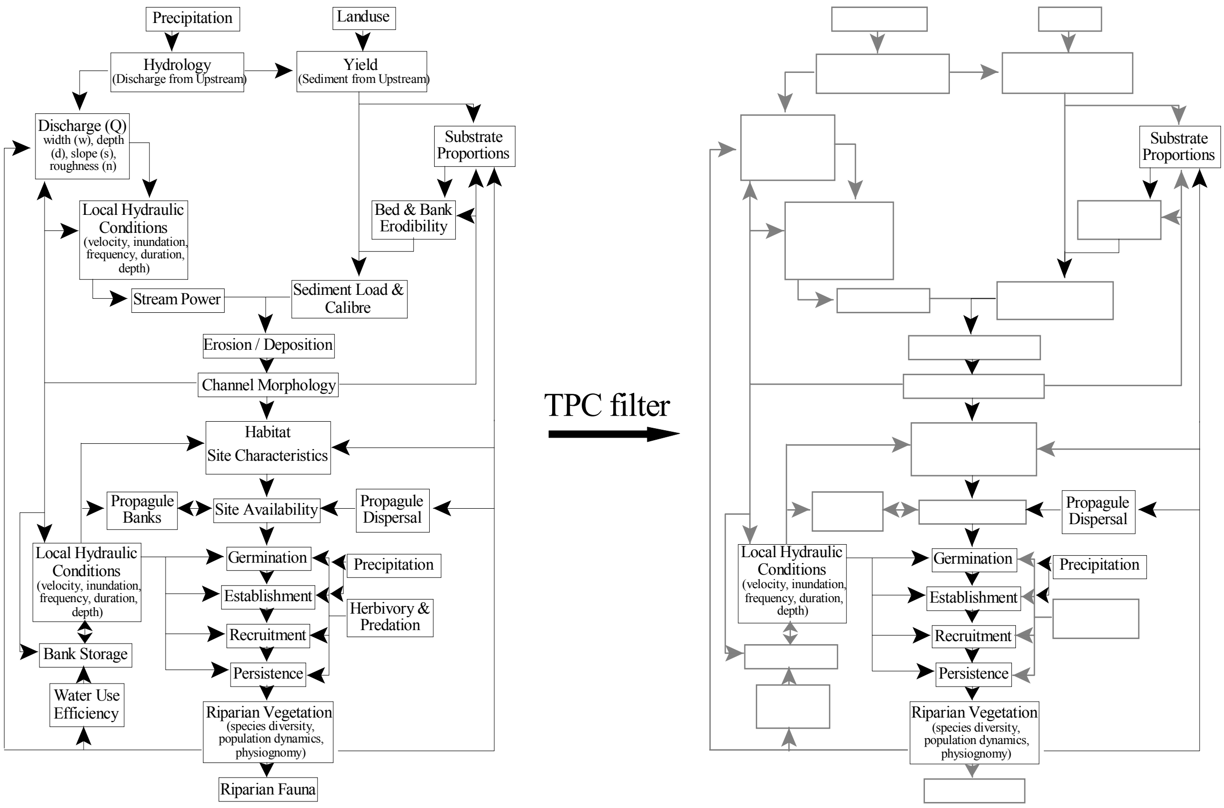

Figure 2.3 An example of the filtering process whereby the unnecessary components of the entire system model are filtered out by the TPC to form the pragmatic model that only includes essential components.

2.2.5 Problem models and TPCs for KNP rivers

As part of the broad vision for the KNP, managers are required to maintain biodiversity (*sensu* Noss, 1990) in all its natural facets and fluxes (Braack, 1997).

With respect to the rivers of the KNP, the principal problem for managers and scientists has been to predict and monitor the response of biodiversity in specific river sections to changes in hydrology, sediment supply and water quality (Rogers and Biggs, 1999). Along the Sabie River these modifications translate into two major areas of potential change that are of concern to managers; altered flow regimes and associated increased sediment storage (Figure 2.4). Managers and scientists together, have identified four key problems associated with increased alluviation and altered flows. These are terrestrialisation of the riparian zone, loss of bedrock

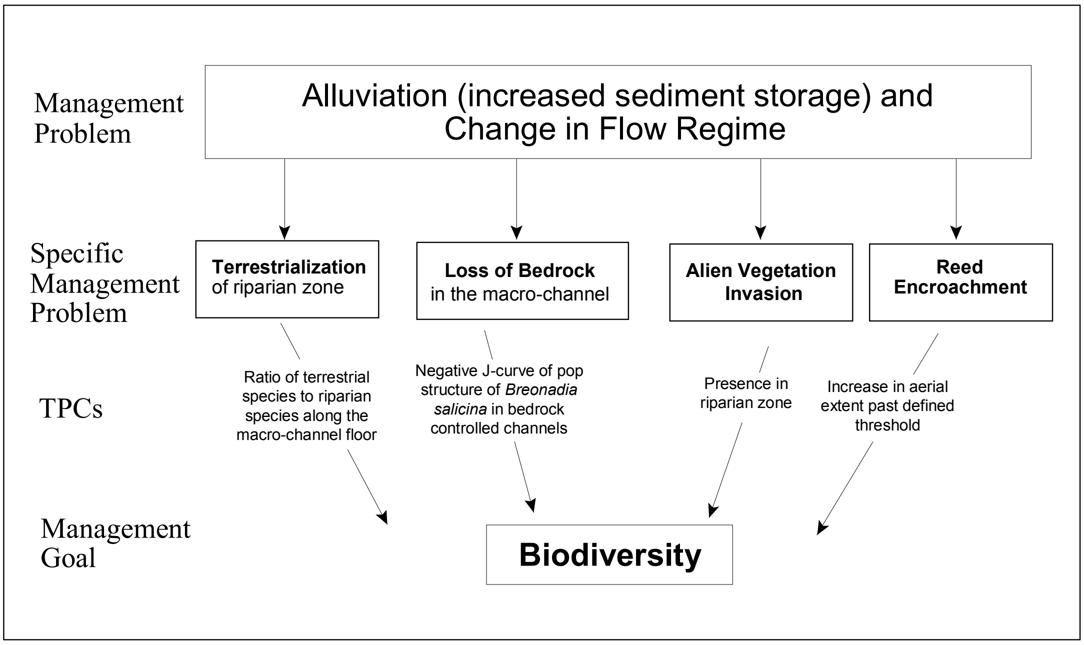

Figure 2.4 Problem models and associated TPCs for KNP rivers.

influence in the macro-channel, invasion of the riparian zone by alien vegetation, and encroachment of reeds. A TPC is assigned to each of these management problems, but their level of development depends on the depth of understanding of the associated problem.

TPC for terrestrialisation of the riparian zone

Terrestrial species typically occur in the savanna, but are also found to occur naturally within the riparian zone, and display a gradient of decreasing abundance as proximity to the active channel increases (van Coller, 1993). While the presence of terrestrial species in the riparian zone increases species diversity, a progressive increase in terrestrial species at the expense of riparian species, which we refer to as terrestrialisation, will decrease overall biodiversity of the riparian zone, and is thus a concern to managers.

We hypothesized that the processes, or agents of change, underlying terrestrialisation are reduced flooding frequency, subsequent reduced water availability from the water table, and increased sediment storage along the macro-channel floor. The ratio of terrestrial species to riparian species typically increases with an increase in distance above and away from the channel as a result of reduced flooding frequency and increased distance from the water table. Because the ratio is dependent on position relative to the active channel, it is appropriate that the ratio is referenced relative to a gradient, which represents a change in both flooding frequency and water table depth. Attention is focussed on trees, since riparian trees are highly dependent on the water table for their persistence (Birkhead *et al.*, 1997).

There are three main ways through which an increase in the ratio of terrestrial species relative to riparian species can occur along a flooding frequency and water table depth gradient. Each signifies the influence of a particular agent of change (Figure 2.5). First the ratio will increase through the loss of riparian species, while terrestrial species abundance remains the same or increases (Figure 2.5 i). This may result from either reduced establishment of riparian species through altered flooding frequencies, or through the loss of established riparian species as a result of severe drought/s. The latter phenomenon was evident during a drought in 1992 when large-scale mortality of individuals of some riparian species occurred (van Coller and Rogers 1996). Prolonged low water table levels, low rainfall, hot temperatures, high evaporative demand, and the influence of bedrock cutting off the water table from the active channel, all contributed to these high levels of mortality. A drought with no rainfall will also prevent the establishment and expansion of terrestrial species.

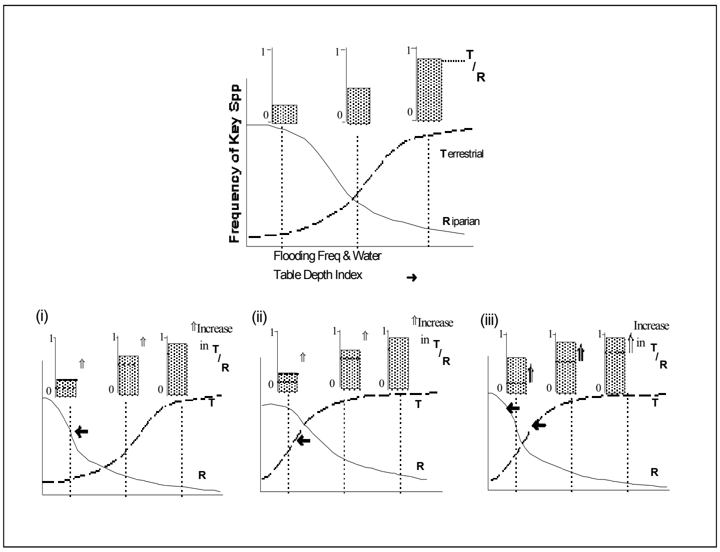

Figure 2.5 Hypothesis of three ways in which the ratio of terrestrial species to riparian species may increase.

Second, the ratio of terrestrial species to riparian species may increase through the increase in the number of terrestrial species while riparian species abundance stays the same or decreases (Figure 2.5ii). The process resulting in such a change is likely to be a reduction in flooding frequency. Terrestrial species not tolerant to flooding or inundation may establish closer to the active channel as they are no longer disturbed as frequently during early life stages when they are most vulnerable. Competition for nutrients, space and light close to the channel where riparian species occur with high cover abundances may act to inhibit terrestrial species from encroaching too close to the channel.

The third way that the ratio may increase is if both riparian species decrease in abundance and terrestrial species increase (Figure 2.5iii). Such changes are likely to occur as a result of severe reductions in flow over a prolonged period due to upstream catchment practices, while rainfall remains normal. Reduced flooding and availability of water from the water table act together to reduce establishment and increase mortality of riparian species as well as allow terrestrial species with higher water use efficiencies to establish closer to the active channel. Rainfall without a high flooding frequency would be an important combined process allowing terrestrial species to become established.

We propose that the TPC for terrestrialisation of the macro-channel floor be a range in the ratio of the abundance of individuals of key terrestrial plant species, to the abundance of individuals of an equal number of key riparian plant species along an index of flow frequency and availability of water from the water table (Figure 2.6). The TPC would incorporate natural flux within the system and alert managers to a potential problem if the limit is exceeded. A major challenge facing the development of such a TPC is establishing a suitable flow frequency-water availability index, as well as the actual range of ratio acceptability.

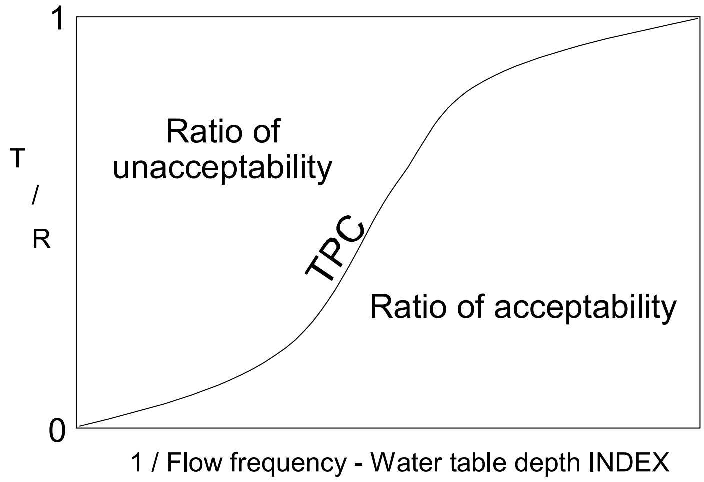

Figure 2.6 A TPC for terrestrialisation represented as a range in the ratio of the abundance of key terrestrial species to the abundance of an equal number of key riparian species along an index of flow frequency and water table depth.

2.3 A DEFINITION OF RIPARIAN ZONES

The term "riparian" is most commonly used in the context of riparian zone (Swanson *et al.*, 1982; Gregory *et al.*, 1991; Naiman and Décamps, 1997) or riparian corridor (Naiman *et al.*, 1993; Rogers and Naiman, 1997). These two terms are used synonymously to describe a three dimensional area of land along a river forming an interface between the aquatic and terrestrial ecosystems (Kovalchik and Chitwood, 1990; Gregory *et al.*, 1991). This zone of transition between these two ecosystems is what is known as an ecotone (Décamps and Naiman, 1990; Holland *et al.*; 1991), since it has a set of characteristics uniquely defined by space and time scales, and by the strength of interaction between the adjacent ecological systems (Holland, 1988). The vegetation of riparian corridors in semi-arid regions is particularly distinctive from the air, where it stands out during the dry season as a dense green belt of vegetation bisecting the sparser brown deciduous vegetation of the terrestrial ecosystem (Hughes, 1994).

Riparian zones provide important and specialized habitat, and increase biological diversity to an extent that is disproportionately high for the area they occupy (Gregory *et al.*, 1991; Franklin, 1992). Riparian zones are also important ecosystems responsible for meeting the primary habitat requirements of many plant and animal species (Franklin, 1992). In addition, they provide intricate links between terrestrial and aquatic ecosystems, and are sensitive enough to provide early indications of environmental change (Gregory *et al.*, 1991;Naiman and Décamps, 1997). Riparian zones are one of the most dynamic ecosystems, and frequent disturbance events result in complex mosaics of landforms and associated biological communities, which are often more heterogeneous and more diverse than those in upland landscapes (Gregory *et al.*, 1991).

Despite riparian corridors being recognisable from a distance, they are difficult to delineate precisely (Gregory *et al.*, 1991). Views differ markedly as to the lateral and vertical extent of the corridor. These different spatial extents are defined in relation to the type and temporal nature of the hydrogeomorphic processes. We adopted the definition of riparian zone in its broadest sense, which encompasses the stream channel and the portion of the terrestrial landscape from the high water mark towards the uplands where vegetation may be influenced by elevated water tables or flooding, and by the ability of soils to hold water (Naiman *et al.*, 1993; Naiman and Décamps, 1997). This therefore incorporates the area of land that extends outwards to the limits of flooding (Gregory *et al.*, 1991) and is theoretically wide enough to cover the different fluvially generated landforms as well as an area of upland (Schaefer and Brown, 1992). Adopting this definition, the lateral and vertical extent of the Sabie River riparian zone includes the area within the confines of the macro-channel extending to the top of each bank, since this is the outward limit of flooding.

2.4 INTERACTIONS BETWEEN VEGETATION, GEOMORPHOLOGY, AND HYDROLOGY

Hydrological and geomorphological processes have a profound effect on riparian vegetation (Auble *et al.*, 1994; van Coller *et al.*, 1997; Auble and Scott, 1998; Ferreira and Stohlgren, 1999; Friedman and Auble, 1999). Patterns of species distribution, richness, and abundance are a result of both fluvial disturbances, and nonfluvial disturbances from adjacent upland areas (Gregory *et al.*, 1991). Patterns of riparian vegetation are influenced by the bedrock geology, geomorphic features, the soil character, climate, and hydrological regimes (Nakamura *et al*, 1997; Tabacchi *et al.* 1998; Merritt and Cooper, 2000). However, there is a reciprocal control between hydrology and vegetation, which can be studied from a geomorphological template (Tabacchi *et al.* 1998).

2.4.1 Interactions between geomorphology and vegetation

Geomorphic processes generally affect the structure and composition of vegetation (Hupp and Osterkamp, 1985; Swanson *et al*, 1988; Auble *et al.*, 1994; Hupp and Osterkamp, 1996; Auble and Scott, 1998; Ferreira and Stohlgren, 1999). The fluvial geomorphology of the Sabie River has been shown to be a critical component in riparian vegetation distribution patterns (van Coller *et al.*, 1997). The Sabie River is a mixed bedrock-alluvial river, and thus has characteristics of both alluvial and bedrock-controlled rivers (van Niekerk and Heritage, 1993; Moon *et al*, 1997), which affect vegetation patterns.

Fluvial geomorphic process (cycles of aggradation and degradation) give rise to a highly complex mosaic of landform patches at different spatial and temporal scales (Hupp and Osterkamp, 1996). In semi-arid regions, the relationship between riparian vegetation distribution patterns and geomorphic landforms is closely related to infrequent flood events that create new sites for the establishment of individuals (Friedman *et al.*, 1996). Thus, in riparian corridors in semi-arid areas, the interactions between vegetation and geomorphology are event driven. The implication for the present study is that greater emphasis was placed on droughts and floods than on intermediate flow, although all are incorporated in the model.

The degree of bedrock influence on each landform of the Sabie River was found to have an overriding control on vegetation patterns (van Coller *et al.*, 1997). Increased sediment supply as a result of land degradation in the catchment, coupled with decreased flow, may increase sediment storage in the river. A change in proportion of sediment to bedrock will affect vegetation distribution patterns.

2.4.2 Interactions between hydrology and vegetation

Hydrology is the most important factor influencing the structure, dynamics, and composition of riparian zones (Auble *et al.*, 1994; Naiman and Décamps, 1997; Friedman and Auble, 1999). Flood frequency, flow duration, and period of inundation are some of the hydrologic factors that are related to vegetation patterns (van Coller *et al.*, 1997; Auble and Scott, 1998; Ferreira and Stohlgren, 1999).

Flooding directly affects plants through inundation, physical damage, and uprooting of individuals, resulting in reduced growth or mortality (Gill, 1970; Frye and Quinn, 1979; Swanson *et al.*, 1982; Rogers and van der Zyl, 1989; Stromberg *et al.* 1991, 1993b; Auble *et al.*, 1997; Auble and Scott, 1998; Ferreira and Stohlgren, 1999). Species differ substantially in their ability to tolerate the effects of flooding (Blom *et al.*, 1990), which is reflected in different species distributions along a flooding frequency gradient (Wissmar and Swanson, 1990; Auble *et al.*, 1994). Floods also create new areas for vegetation colonization (Wissmar and Swanson, 1990), and disperse seeds. Riparian vegetation is maintained by periodic flooding (Hupp and Osterkamp, 1985), and a modification of flooding regimes could result in a decline in certain riparian species populations, or cause a population shift to more suitable locations (Merritt and Cooper, 2000). The Sabie River is characterised by extreme discharge events, and even during drought periods occasional floods can occur (Heritage and van Niekerk, 1995). Periodic exposure to hydrological disturbances results in riparian zones being dynamic landscapes, with high species diversity (Tabacchi, 1995).

There is a strong relationship between species composition and elevation above the channel floor (Hupp and Osterkamp, 1985; Nakamura *et al*, 1997). Elevation affects flooding frequency, soil texture, and soil moisture, which in turn affect species composition (Nakamura *et al*, 1997). Minor elevational differences are directly related to major variation in hydrologic processes (Hupp and Osterkamp, 1985).

Distance from the channel also affects flooding frequency and intensity (Nakamura *et al*, 1997). Vegetation distribution patterns along the Sabie River are closely linked to elevation above and horizontal distance away from the active channel (van Coller *et al*, 2000). The strong influence of elevation is due to the sharp increase in elevation of the macro-channel bank above the macro-channel floor (van Coller *et al*, 2000). There is a gradient from hydraulically dominated vegetation that is tolerant of flooding, to hydrologically dominated vegetation that is intolerant of flooding and requires access to water from the water table, with an increase in elevation above the active channel (van Coller *et al*, 2000). This gradient is based on the relationship between elevation and flooding frequency, and the distance to the water table. Tree species on active sites are subject to frequent flooding, which may retard development. Species that are intolerant of flooding are unable to establish in these areas. Further away from the channel floor inundation occurs less frequently, rendering the area more stable, and allowing terrestrial species to become established (Nakamura *et al*, 1997).

Droughts affect sediment translocation and deposition, altering the flow regime of the river (Heritage and van Niekerk, 1995; Tabacchi, 1995). Both riparian and terrestrial species are affected by droughts, and many trees died along the Sabie River during the extreme drought that occurred in 1992 (van Coller and Rogers, 1996). In general, however, terrestrial species are less water dependent, and more tolerant of dry periods than are riparian species. After severe droughts or floods, the local seed bank may play a major role in the recovery of various populations (Tabacchi, 1995). However, in semi-arid regions establishment is often limited by water availability (Hughes, 1988).

Many factors influence the recruitment of plants (Grubb, 1977; McBride and Strahan, 1984; Cordes *et al.*, 1997) but the frequency and intensity of flooding is particularly important during the regeneration phase of riparian plant populations (Streng *et al.*, 1989; Nakamura *et al*, 1997). As flooding plays a key role during germination and establishment, the phenology of plant species relative to the timing of floods is of great importance (Tissue and Wright, 1995; MacKenzie, *In prep.*).

The depth to the water table is especially important during the establishment phase of germinants, and the rate of water table decline following overbank flows is a key determinant of the probability of survival of germinants and seedlings (Manders and Smith, 1992). A rapid decline in the level of the water table may be too fast for the growth rates of the roots of germinants. This phenomenon is particularly true in riparian corridors in semi-arid regions where rainfall events are extreme and infrequent, hydrological regimes are variable and flashy, and sediments often do not hold water very well. Rivers such as the Sabie, however, show greater complexity because the presence of bedrock influences the dynamics and structure of the water table. Perched water tables, which need to be recharged by flooding events, often exist.

Fluctuations in the groundwater table in river banks are often directly associated with fluctuations of water levels in the river (Birkhead *et al.*, 1996). Water availability from the water table is regarded as a major limiting resource to riparian plant species (Adams, 1989), influencing growth, performance, and survival. This is especially true of woody riparian and terrestrial species that are rooted in the water table (Smith *et* *al.*, 1991; Ellery *et al.*, 1993). The edge of a riparian woodland in a semi-arid region of Kenya was found to be closely associated with a dramatic decline in the water table levels (Hughes, 1987). Woody riparian species have little resistence to drought stress, since they need to obtain sufficient water to compensate for their large daily transpirational losses (Smith *et al.*, 1991; Birkhead *et al.*, 1997). An inability to obtain this water due to drought or unnatural flow regulation, will in many cases lead to extreme stress in trees which may result in mortality (van Coller and Rogers, 1996). Terrestrial species are less susceptible to altered flow regimes, and are more likely to survive droughts than are riparian species.

2.4.3 The effect of vegetation on hydrology and geomorphology

As discussed, hydrology and geomorphology affect vegetation distribution patterns. However, vegetation also exerts an influence on both of these phenomena. Vegetation affects structure by establishing in cracks on rocks (e.g. *Breonadia salicina*), and colonising sand bars (e.g. reeds). This change in structure in turn affects both hydraulics and geomorphology by reducing flow rates and increasing sedimentation (Breen *et al*. 2000). Thus riparian vegetation influences the morphology of the river (James *et al.*, 1996), and is an integral component of the fluvial system (Hupp and Osterkamp, 1985; Elmore, 1992).

Riparian vegetation also exerts a significant influence on fluvial processes through its effect on light, temperature, and evapotranspiration (Naiman *et al.*, 1993; Tabacchi *et al.* 1998), which affect the hydrological cycle. Riparian vegetation therefore has a feedback effect on the hydrological cycle.

Riparian vegetation reduces water velocities, and enables the removal of suspended sediment from surface water (Tabacchi *et al.* 1998). It is also a source of woody debris, which affects sedimentation processes, channel morphology, and instream habitat (Gregory *et al.*, 1991; Naiman *et al.*, 1993). During floods, the woody debris and riparian vegetation significantly affect flow by increasing roughness (Gregory *et al.*, 1991; Tabacchi *et al.* 1998). Riparian vegetation thus has a significant effect on fluvial processes such as flow, channel morphology, and sedimentation.

2.5 THE RIPARIAN-TERRESTRIAL INTERFACE

The roles of riparian vegetation on terrestrial ecosystems and *vice versa* have not been explored in much detail. Little is known about the structure and functioning of ecotones at the terrestrial-riparian interface compared with those in lakes and oceans, or typical terrestrial ecosystems (Pieczyńska, 1990; Tabacchi *et al.* 1998).

Riparian zones form the boundary between terrestrial and aquatic ecosystems, and as such they contain distinct gradients of environmental factors, ecological processes, and vegetation communities, as well as showing spatial and temporal instability (Pinay *et al*, 1990; Gregory *et al.*, 1991). However, terrestrial ecosystems have a profound effect on riparian ecosystems (Elmore, 1992), and there are numerous ecological linkages between the two ecosystems (Franklin, 1992). Geomorphic and disturbance processes from both the terrestrial area and the river affect the riparian zone, influencing the spatial pattern of riparian vegetation (Gregory *et al.*, 1991).

Size, frequency, and duration of floods decrease with increasing distance from the active channel, and riparian and terrestrial vegetation reflects this disturbance regime (Gregory *et al.*, 1991). Terrestrial species cannot become established close to the active channel because of the effects of frequent flooding (surface erosion, periodic inundation, *etc.*) (Gregory *et al.*, 1991). However, during periods of low flow the exposed active channel is colonized by seedlings of terrestrial shrubs and trees (Gregory *et al.*, 1991). These may not survive if they become inundated during high flow.

The slopes of the macro-channel bank along the Sabie River experience low flooding frequencies, and are stable and subject to little sedimentation and erosion (van Coller *et al.*, 1997), allowing the establishment of terrestrial individuals. Relative to the macro-channel floor there is reduced water availability from the water table, and the vegetation that occurs on the macro-channel banks is generally more tolerant of drought stress, and less tolerant of flooding conditions than vegetation occurring on the macro-channel floor (van Coller *et al.*, 1997).

Heavy browsing can also cause a deterioration in the condition of riparian vegetation (Elmore, 1992), and may increase the opportunity for the establishment of terrestrial species which are tolerant of heavy browsing (such as *Dichrostachys cinerea*). If these individuals are not removed or killed by high flows or floods, they can lead to problems through colonization of the riparian zone. Reduced flow or a lowered water table is expected to exacerbate the problem.

Plantations of exotic species use more water than indigenous vegetation. Plantations cause a significant reduction in runoff to rivers, resulting in reduced water tables and reductions in river flow, especially during dry months and periods of drought (Moon *et al*, 1997). This impacts on vegetation structure in the riparian zone, for example affecting the ratio of terrestrial to riparian species. The ratio is defined along an index of flow frequency and water table depth, and a change in watertable depth would therefore be expected to affect the ratio. The reduction of groundwater results in the loss and alteration of riparian vegetation, especially in arid and semiarid regions (Stromberg *et al*, 1996), and this may make opportunities available for terrestrial species that are less water dependent (such as *D. cinerea* and *Acacia nigrescens*) to become established.

CHAPTER 3

METHODOLOGY

This chapter contains a brief description of the methods used to collect the field data. The data were used to develop rules in the model, as discussed in Chapter 5. Specific methods in model development and planning are given in Chapter 5. Monitoring is necessary to test and refine the model, and this is discussed in detail in Chapter 7.

3.1 SPECIES SELECTION

Complex population modelling prohibits the use of all species. Therefore, before data collection could begin we had to choose and justify the choice of key riparian and terrestrial species. In a detailed study conducted along the Sabie River by van Coller (1993), riparian species abundance was related to elevation above the active channel. Based on his results, we selected riparian species to best represent the range of hydrogeomorphic features (Table 3.1), excluding those species that occur on bedrock, as upland species do not compete for these sites. *Syzygium guineense* (Water Pear) and *Combretum erythrophyllum* (River Bushwillow) were thus chosen as key riparian species.

Table 3.1 Flooding characteristics of actively, seasonally, and ephemerally flooded geomorphic units (van Coller *et al.*, 1995).

Flow	Annual Maximum Flow Data (Years)			Daily Average Flow Data (Days)		
Category	Channels Activation	Overtopping	Bars Inundation	Channels Activation	Overtopping	Bars Inundation
Active	1	1-2	1-2	Always	1-14	>350
Seasonal	1-2	1-2	1-3	1-14	1-7	<15
Ephemeral	2-4	2-6	3-6	<1	<<1	<<1

We conducted a preliminary study to investigate a number of potential woody terrestrial species. Transects were extended 60m from the top of the macro-channel bank into the upland area. Along each, the number of various species was recorded at increasing distances from the macro-channel bank. Resulting curves showed the change in numbers of individuals for different species with horizontal distance or elevation above the active channel. Three general patterns were observed:

1. riparian species that occurred exclusively in the riparian zone,
2. boundary species that occurred higher and further away from the active channel in the riparian zone, and extended in decreasing number into the uplands, and
3. terrestrial species that occurred higher and further away from the active channel in the riparian zone, and extended well into the uplands, often increasing in number in the upland areas.

Within the terrestrial species group, we excluded species that occurred in low abundance, and thus selected *Dichrostachys cinerea* (Sickle Bush) and *Acacia nigrescens* (Knob Thorn) as key terrestrial species.

3.2 DATA COLLECTION

Data were collected along 19 transects, which extended from the active channel to the top of the macro-channel bank. The transects used were those established by van Niekerk and Heritage (1993), as the geomorphology of these areas has been described (van Niekerk and Heritage, 1993), and exists in a relational database. Transects were 20m wide, and were divided into contiguous plots based on geomorphological units. Baseline data were collected in October 1999, and the transects were resampled in October 2000 and July 2001.

Along each transect, every individual of the two key riparian species (*C. erythrophyllum* and *S. guineense*) and the two key terrestrial species (*A. nigrescens* and *D. cinerea*) was recorded, and its stage class noted. Stage classes comprised germinants (individuals with cotyledons), seedlings, saplings, young adults (individuals that were old enough to begin flowering), mature adults (individuals that were able to produce abundant flowers) and senescent adults (individuals that were no longer able to flower to their full extent). During the baseline survey in 1999, the nearest neighbour (woody species) and its stage class were also recorded, and the distance between them was measured as an indication of competition.

In addition, a minimum of 40 individuals of each species was marked. The stem circumference of marked individuals was measured, and stem diameter calculated. In adults, stem circumference was measured at breast height, to enable the calculation of DBH (diameter at breast height). For seedlings and saplings, stem circumference was measured just above ground level. Marked individuals were re-sampled to obtain measures of growth rates. At least 20 seedlings and saplings, and at least 20 young and mature adults (of each species) were marked. Germinants and senescent adults were not marked.

We compared numbers of individuals of the two terrestrial and two riparian species on features subject to different categories of flow (actively, seasonally, and ephemerally flooded geomorphic features (Table 3.1)). In addition, colonization was investigated at different levels of the geomorphic hierarchy, as geomorphic features are formed by and associated with specific flows. Channel types and geomorphic units were the two levels investigated. Analysis of Variance was performed using SYSTAT, and Tukey's test was used to determine where significance occurred. Where necessary, data were log transformed.

CHAPTER 4

TERRESTRIALISATION RESULTS

The results of the data collection described in Chapter 3 are presented below. These results are based on data collected in the field. Analysis of model output is discussed in Chapter 6, and the results of the *Breonadia* Model monitoring are discussed in Chapter 7.

4.1 HYDROLOGICAL INFLUENCE

Numbers of terrestrial individuals occurring in different positions on the geomorphic template differed significantly over all years (p = 0.005; 0.002; 0.0003 in 1999, 2000 and 2001respectively) and were an order of magnitude higher on ephemerally flooded features than on actively or seasonally flooded features (Figure 4.1). The 2000 flood reduced the number of riparian individuals on actively and seasonally flooded features, whereas the number on ephemerally flooded features remained relatively constant. The number of terrestrial individuals was reduced on all features. Sites with a history of frequent flooding supported greater numbers of riparian individuals, whereas sites that were infrequently flooded afforded greater resilience to the flood. The number of terrestrial individuals increased along a gradient of decreasing flooding frequency, and the catastrophic flood of 2000 did not affect this trend. This suggests that frequent flooding has a greater limiting effect on terrestrialisation than do large, infrequent floods.

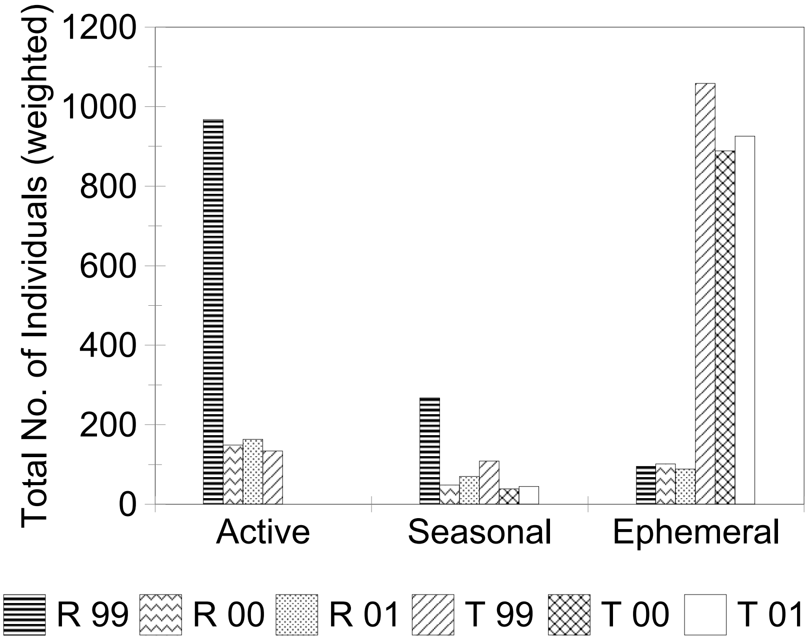

Figure 4.1 Total numbers of individuals of riparian (R) and terrestrial (T) species recorded on geomorphic features subject to different flow regimes, in 1999, 2000, and 2001.

Ratios of terrestrial to riparian individuals were also an order of magnitude higher on ephemerally flooded features than on actively or seasonally flooded features, on which the ratio was below 1 in all years (Figure 4.2). The ratio decreased on both actively and ephemerally flooded features after the flood in 2000, and increased slightly on seasonally flooded features immediately after the flood, before dropping in the following year. Results suggest that frequent flooding (seasonally or more) limits terrestrialisation of the riparian zone.

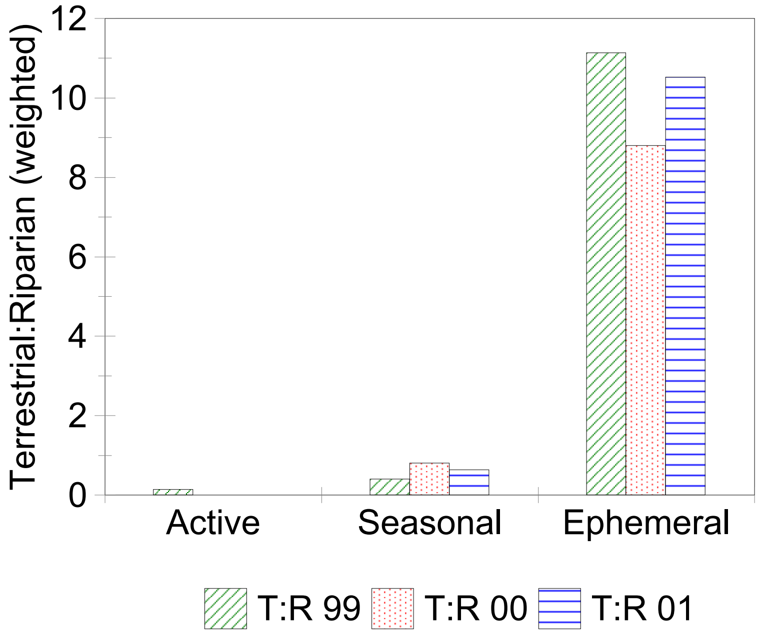

Figure 4.2 Ratio of terrestrial to riparian individuals on geomorphic features subject to different flow regimes, in 1999, 2000, and 2001.

We used the fact that vegetation distribution was significantly different depending on position on the geomorphic template and consequent flooding frequency, to develop rules for the model. Based on the results, we made rules of probability of occurrence and survival depending on the individual's position on the geomorphic template.

4.2 CHANNEL MORPHOLOGY

T:R ratios using all plots except the macro-channel bank (because only macro-channel floor features define channel types (van Niekerk and Heritage, 1993)) revealed that pool-rapid channels were most invaded by terrestrial individuals, followed by braided and mixed anastomosing channels (Figure 4.3). Bedrock anastomosing channels were least invaded. This was true in both 1999 and 2000, but there was no ratio for pool-rapid channels in 2001 because of the death of all remaining terrestrial individuals. These observations were used to define probability of occurrence rules in the model. Similarity of T:R ratios on different features of the macro-channel floor indicated that channel type played a less pronounced role in terrestrial invasion of the riparian zone than did flooding frequency.

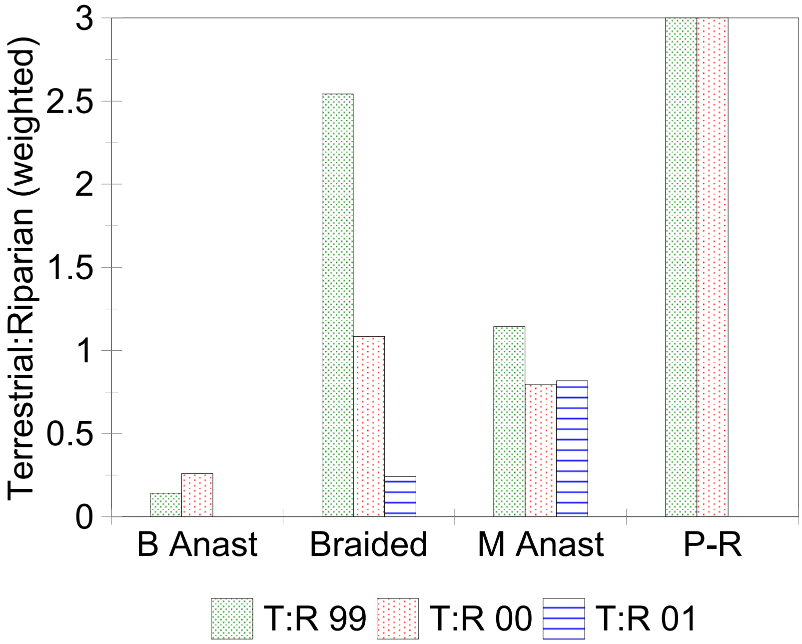

Figure 4.3 Ratio of terrestrial to riparian individuals in each channel type (B Anast: bedrock anastomosing, M Anast: mixed anastomosing, P-R: pool-rapid) in 1999, 2000, and 2001.

A complete interpretation of ratios, however, requires that absolute numbers also be considered. In all years, most terrestrial individuals occurred in braided channels (which are characterized by alluvium), and least in bedrock anastomosing (which are characterized by exposed bedrock) and pool-rapid channels (Figure 4.4). Most riparian individuals occurred in bedrock anastomosing channels, and least in pool-rapid channels. In 1999, low numbers of terrestrial individuals in bedrock anastomosing channels resulted in a small T:R ratio, and almost equal numbers of terrestrial and riparian individuals in mixed anastomosing channels resulted in a T:R ratio close to 1. In pool-rapid channels the ratio was high in 1999 and 2000, but this is deceptive as this channel type is least sensitive to terrestrialisation, but supports low numbers of riparian individuals, which resulted in the high ratio observed (Figures 4.3 and 4.4). We thus decided on the presence of a minimum of ten individuals in order to calculate a ratio. Below this number, a meaningful ratio cannot be determined and absolute numbers must rather be considered.

Results show that in the Sabie River, terrestrial invasion at the channel type scale is limited by high proportions of bedrock, and facilitated by high proportions of sediment. Braided channels are thus most susceptible, and bedrock anastomosing and pool-rapid channels least susceptible, to invasion by terrestrial individuals.

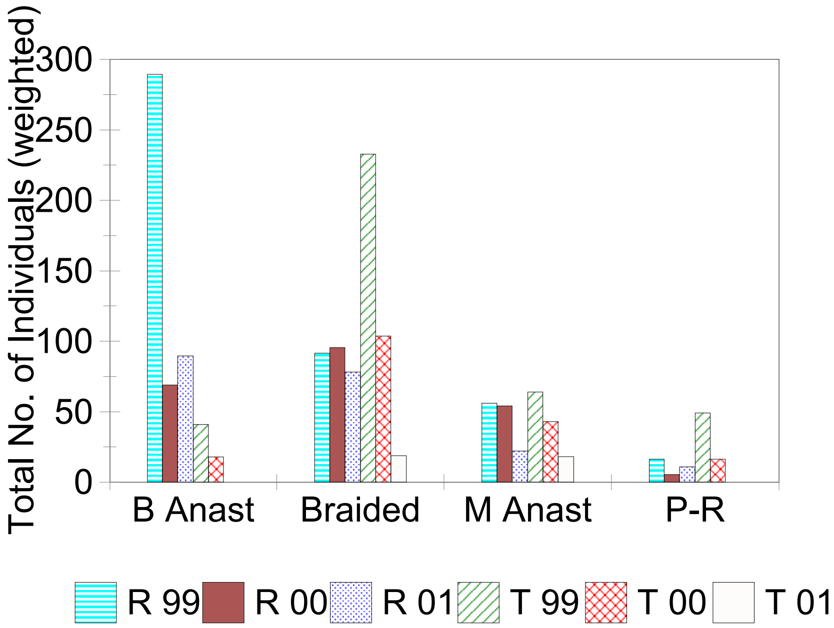

Figure 4.4 Total numbers of riparian (R) and terrestrial (T) individuals in each channel type (B Anast: bedrock anastomosing, M Anast: mixed anastomosing, P-R: pool-rapid) in 1999, 2000, and 2001.

The number of riparian and terrestrial individuals decreased in all channel types following the catastrophic flood of February 2000 (Figure 4.4). The rate of decline for terrestrial species was greatest in braided channels, and for riparian individuals was greatest in bedrock anastomosing channels. The rate of decline of riparian individuals was less than that of terrestrial individuals, on all channel types except bedrock anastomosing. The effect of the 2000 flood on vegetation distribution appeared to be dependent on channel morphology, and this effect differed for terrestrial and riparian species.

4.3 GEOMORPHIC UNITS

T:R ratios indicated that the macro-channel bank was markedly more invaded by terrestrial individuals than other geomorphic units (Table 4.1). Along the macro-channel floor, T:R ratios indicated that islands, lateral bars, and alluvial and mixed distributaries were most invaded by terrestrial individuals. All geomorphic units with high T:R ratios were characterized by alluvial sediments, and all geomorphic units characterized by bedrock had low T:R ratios. The effect of geomorphic units on terrestrialisation of the riparian zone indicates that, along the Sabie River, sediment is an important determinant of where terrestrial individuals can colonize and persist.

In each of the three years, the number of riparian individuals differed significantly from the number of terrestrial individuals on each geomorphic unit ($p < 0.0005$). This result can be explained by the large numbers of terrestrial individuals and the small numbers of riparian individuals recorded on the macro-channel bank, compared to any other geomorphic unit (Table 4.1). A Tukey test revealed that the significant differences were always between the macro-channel bank and some other feature. When the macro-channel bank was excluded from the test, no significant differences were found, in any year, for either terrestrial or riparian species.

Table 4.1 Total numbers of terrestrial and riparian individuals on different geomorphic units. T: terrestrial individuals, R: riparian individuals; in 1999, 2000 and 2001).

Category of flow	Geomorphic unit	T 99	R 99	T:R 99	T 00	R 00	T:R 00	T 01	R 01	T:R 01
Active	Bedrock core bar	0	30	0	0	0	0	0	5	0
	Channel bedrock	0	0	0	0	2	0	0	0	0
	Lateral bar	9	32	0.28	0	8	0	0	6	0
Seasonal	Alluvial distributary	0	3	0	0	0	0	0	0	0
	Bedrock core bar	4	13	0.31	0	5	0	0	9	0
	Lateral bar	19	54	0.35	11	8	1.38	13	8	1.63
	Mixed distributary	12	14	0.86	1	2	0.5	1	5	0.2
Ephemeral	Alluvial distributary	6	1	6	0	2	0	0	0	0
	Bedrock core bar	0	25	0	0	8	0	0	11	0
	Bedrock pavement	0	5	0	0	1	0	0	1	0
	Island	28	11	2.55	5	12	0.42	0	17	0
	Lateral bar	162	52	3.12	9	54	0.17	13	50	0.26
	Mixed distributary	6	0	0	0	0	0	0	0	0
	Macro-channel bank	855	1	855	875	6	145.8	908	2	454
	Terrace	0	3	0	0	18	0	0	12	0

Riparian individuals occurred across a greater range of geomorphic units than did terrestrial individuals. The flood of 2000 reduced the number of terrestrial and riparian individuals on all geomorphic units. The only exceptions were the macro-channel bank, on which the number of terrestrial individuals increased, and ephemeral lateral bars, on which the number of riparian individuals remained constant (Table 4.1).

4.4 POPULATION CHARACTERISTICS

The flood of 2000 was large enough to inundate the ephemerally flooded features, and thus had a strong impact on population structure. The flood reduced the number of adult individuals of all species (Figure 4.5). Adults of *S. guineense* were most seriously affected, as many of the sand bars close to the active channel, on which the majority of individuals occurred, were washed away. Although a large number of *S. guinnense* seedlings germinated after the flood, many did not survive. This was the result of germinating in unfavourable sites which had sufficient moisture immediately

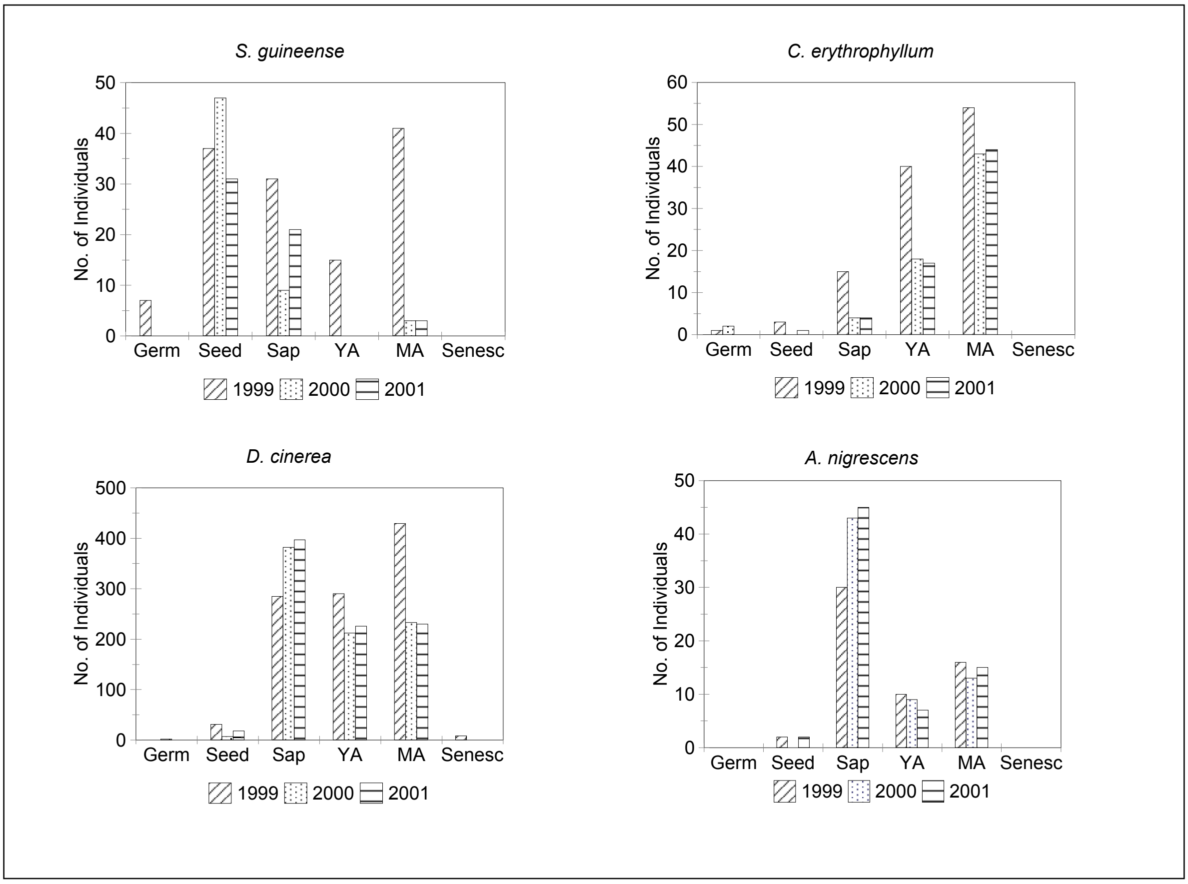

Figure 4.5 Population structure of the four key species for all 3 years. Germ: germinants, Seed: seedlings, Sap: saplings, YA: young adults, MA: mature adults, Senesc: senescent adults.

after the flood, but which soon dried out, resulting in the death of the seedlings. Although terrestrial individuals are intolerant of flooding, they have large, persistent seedbanks which allow them to recruit rapidly after a disturbance. The number of saplings of both terrestrial species increased following the flood. Thus, although many *Dichrostachys cinerea* adults died as a result of flooding disturbance, the high recruitment rate of this species means that terrestrialisation will not necessarily be curbed by floods in the short term. Monitoring will reveal how the T:R ratio changes in the long term, following a 1 in a 100 year flood.

The population structure of *Acacia nigrescens, D. cinerea,* and *S. guineense* changed from an older, to a younger population as the number of juveniles increased after the flood, and the number of adults decreased (Figure 4.5). Only *Combretum erythrophyllum* showed little change in population structure following the flood, although the number of young adults was reduced. This species occurs on lateral bars, and unlike *S. guineense* which occurs on active features close to the active channel, few mature adults were killed or removed by the flood. Overall, with the exception of *C. erythrophyllum*, the flood and post-flood recruitment reduced the average age of the population.

4.5 GROWTH RATES AND SURVIVAL

Growth rates and survival probabilities to be used by the model were calculated from marked individuals. However, due to the catastrophic flood, many of the marked individuals were killed. This resulted in exceptionally low growth rates and survival values, as well as certain gaps in the data where no values could be calculated. It is important that this information is obtained through the monitoring programme.

Separate survival probabilities were calculated for adults and juveniles of each species, as well as for each category of flow (active, seasonal and ephemeral). Values were calculated for each extreme hydrological event as defined by the model (catastrophic floods (Table 4.2), large floods, small floods, droughts, and no-flow events). Default values were calculated for non-extreme hydrological events.

Table 4.2 Survival probabilities for juveniles and adults of each species on each category of flow, calculated for catastrophic floods.

		Active	Seasonal	Ephemeral
A. nigrescens	Juveniles	0	0	0.84
	Adults	0	0	0.58
D. cinerea	Juveniles	0	0	0.09
	Adults	0	0	0.35
C. erythrophyllum	Juveniles	0	0	0.11
	Adults	0	0.1	0.38
S. guineense	Juveniles	0.09	0	0
	Adults	0	0.33	0.17

4.6 HISTORICAL CHANGES

Our data can be compared with those collected by van Coller to cover a wider time span. He collected data on various transects along the Sabie River, in 1993 (after a severe drought), and in 1996 (after a large flood). Although the actual transects differed, all the data were collected along the Sabie River and useful comparisons can thus be made.

In 1993 the ratio of terrestrial to riparian individuals was 0.339 (111:327). In 1996, after the flood, the ratio remained similar at 0.299 (93/311), although the number of individuals was reduced. By 1999 however, the T:R ratio had increased to 4.512 (1101:244). The large increase in ratio can be attributed to the marked increase in terrestrial individuals during this time. We hypothesize that although terrestrial individuals are susceptible to flooding disturbance, they are able to recruit rapidly afterwards because of persistent seedbanks. The ratio increased again after the 2000 floods to 7.151 (901:126). This was mainly a result of more riparian than terrestrial individuals being removed by the flood (Figure 4.5). In 2001 the ratio was 7.769 (940:121). This slight increase was probably due to more rapid recruitment of terrestrial than riparian individuals (Figure 4.5).

CHAPTER 5

CONCEPTUALIZATION AND STRUCTURE OF THE TERRESTRIALISATION MODEL

5.1 MODEL CONCEPTUALIZATION

The filtering process discussed in section 2.2.4 demonstrates the usefulness of the TPC in formulation of a pragmatic model that only includes the essential components required to address a specific problem. In this section we present a pragmatic model for terrestrialisation of the riparian zone.

The life cycles of key riparian and key terrestrial species are the two main biotic components to the pragmatic terrestrialisation model (Figure 5.1). The life cycles of each group include germination on available sites, establishment and persistence of individuals, and feedback via propagule production, dispersal and dormancy. Each stage of the life cycle of the two groups is influenced by key processes, these being availability of water from the water table, flow frequency, precipitation, herbivory, and competition. The degree of influence of these processes will depend on where along a gradient of flow frequency and water availability an individual occurs, whether an individual is riparian or terrestrial, and its life stage or size class.

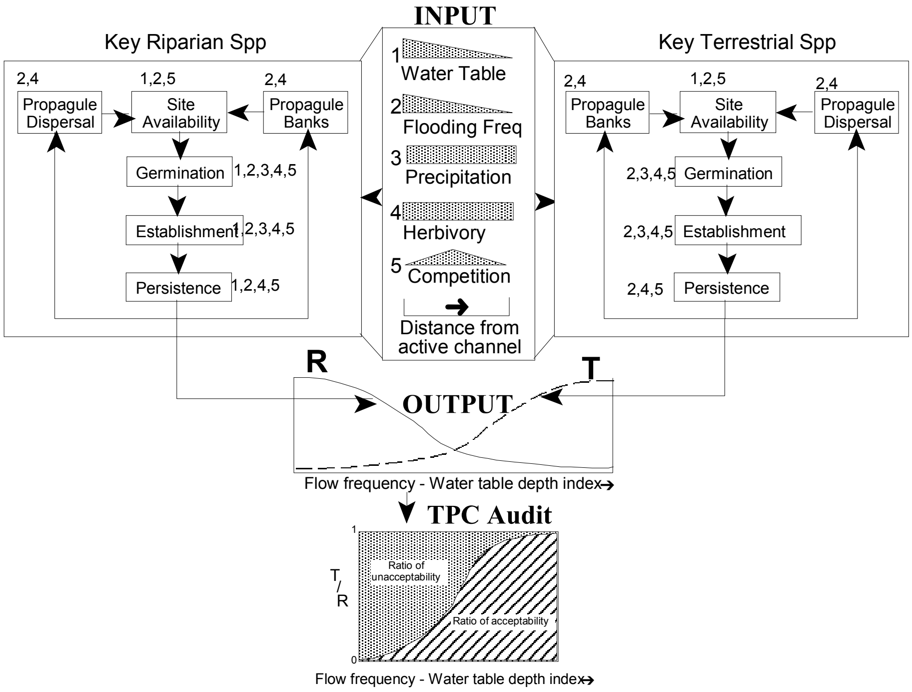

Figure 5.1 Conceptualization of the pragmatic model for the TPC of terrestrialisation of the riparian zone. Inputs and outputs of the model are shown. The numbers in the key riparian and terrestrial species boxes correspond to the numbers in the input box. T and R are terrestrial and riparian species respectively.

The interaction of key riparian and terrestrial species with these five processes will result in differential establishment and persistence of individuals of riparian and terrestrial species along a gradient of flow frequency and water availability in the riparian zone. Resultant response curves along this gradient can therefore be established for key riparian and terrestrial species (Figure 5.1). These two response curves provide the basis for calculating the ratio of terrestrial relative to riparian species, which can be used to audit the TPC.

We conceptualized modelling the dynamics of key riparian and terrestrial species as modularized population models (Figure 5.2). The advantages of modularization are well known (Acocks and Reynolds, 1997) and it lends itself well to Visual Basic, which we used for coding the model. Physical environmental variables for each population are rainfall and hydrology, which affect site quality. Site quality determines the success of germination, mediates growth and survival, and affects dispersal. Dispersal may contribute directly to germination or maintain seed banks. Biotic interactions that are important for growth, survival and dispersal are herbivory and competition.

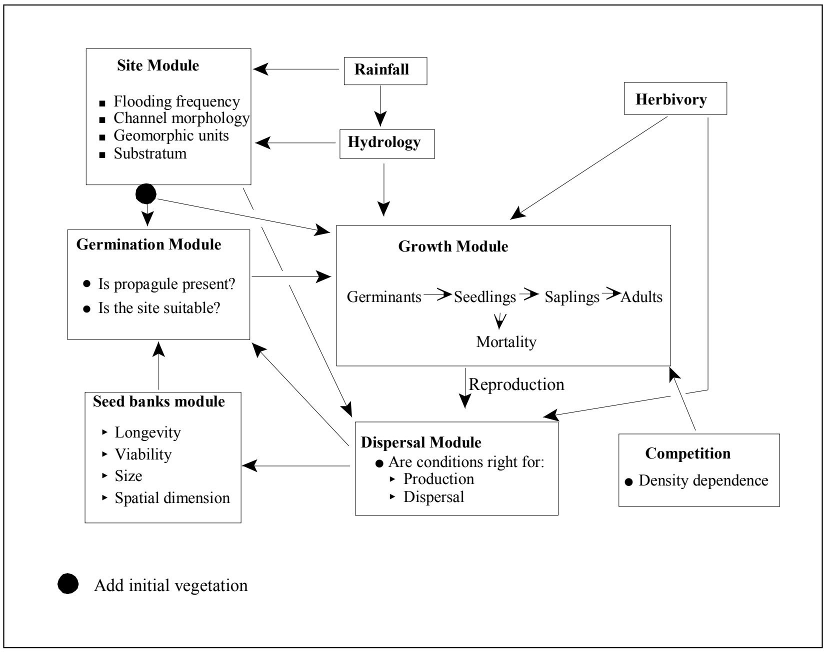

Figure 5.2 Conceptual model of population dynamics for each key species in the terrestrialisation TPC. Boxes represent modules in the model, and arrows represent inputs, feedbacks and processes.

While the terrestrialisation model in its conceptual form (Figure 5.2) incorporates most population processes, assumptions will have to be made in the actual model. This is because of the lack of data and the difficulty of obtaining it in the current project. Examples of this are herbivory and competition.

5.2 MODEL STRUCTURE

The TERRESTRIALISATION Model is a modularised, spatially explicit, individual- and rule-based population model of four key species that occur in the riparian zone of rivers in the Kruger National Park. Modules operate as distinct entities with individual internal structure, and communication between modules occurs as inputs from and outputs to other modules (Figure 5.2).

5.3 MODEL INPUTS

The rainfall, hydrology and site modules together form abiotic input into the biotic components of the model, whereas the addition of initial vegetation, the dispersal, seed bank, herbivory and competition modules are biotic inputs (Figure 5.2).

5.3.1 Rainfall

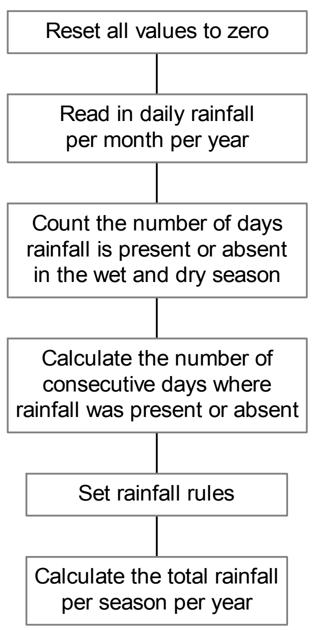

Figure 5.3 Development process of the rainfall module.

The rainfall module (Figure 5.3) is initialised by setting all rainfall data in arrays to zero. Daily rainfall data per month per year is then captured from a text file for as many years as data exist. Any scenario may be opened for assessment. Rainfall periodicity is calculated by counting the number of days where rainfall is present and absent in both the wet and dry season, and determining the consecutive period for rainfall presence and absence. These periodicities are used to set rainfall rules which form direct inputs to the site and growth modules where they affect site quality and survival respectively, and indirect inputs to the germination module, where dormancy is affected (Figure 5.2). Seven or more consecutive days of rainfall presence results in germination of seeds, while 21 or more consecutive days of rainfall absence results in the death of new germinants. Germination of seeds also occurs if a minimum of 7 rain events occurs within 14 days. Finally, the total rainfall is calculated per season per year for graphical display and interpretation of species population response curves.

5.3.2 Hydrology

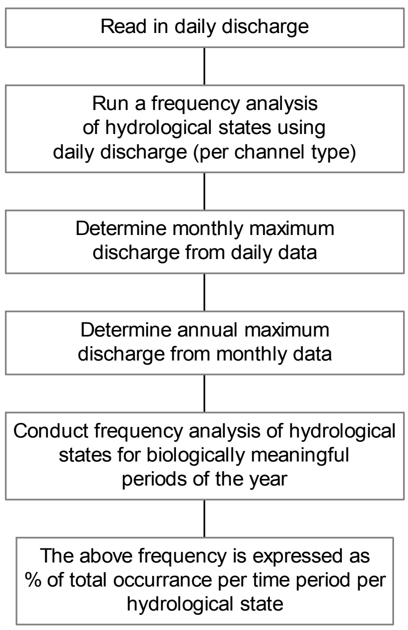

Figure 5.4 Development process of the hydrology module.

The hydrology module starts by reading in daily discharge values of a selected scenario (Figure 5.4). Once again, any scenario may be loaded for assessment. A frequency analysis of predefined hydrological states (Table 5.1) using daily discharge values is then conducted for each month of scenario data. This is done separately for each channel type since hydrological states are dependent on channel morphology. Both monthly and annual maximum discharges are also determined. Frequency analyses of hydrological states are then summated for biologically meaningful periods of the year and expressed as a percentage of the total occurrence per time period per hydrological state. Biologically meaningful time periods are the total year, the wet and dry season, summer and winter, and individual months in the growing season.

Table 5.1 Definition of hydrological states.

	Hydrological state	Inundation frequency	Description
1	No-flow	-------	No flow in river, only standing water in pools
2	Extreme low flows	Active	Minimal amount of water needed for flow in river
3	Base flows	Active	Activation* of active features, but no inundation of active bars
4	Intermediate flows	Seasonal	Inundation of active features and activation* of seasonal features
5	High flows	Seasonal	Inundation of about 50% of seasonal features and activation* of remaining seasonal features
6	Very small floods	Ephemeral	Inundation of seasonal features and activation* of ephemeral features
7	Small floods	Ephemeral	Inundation of about 30% of ephemeral features
8	Large floods	Ephemeral	Inundation of about 50% of ephemeral features
9	Catastrophic floods	Ephemeral	Inundation of about 100% of ephemeral features (bank full flow)

*: activation is defined as the amount of water needed to just reach the feature and moisten it, but not inundate it.

5.3.3 Geomorphology

The site module loads data of a geomorphic template based on data collected by Rountree (1997). Either 1986 or 1996 data may be used to construct the template, which is a section of the Sabie River that varies in size. Each 20x20 m grid is divided into four 5x5 m grids and the same values for channel type, geomorphic unit, and flow category are assigned. The template is displayed spatially to the user using coloured pixels explained in a legend. The site module stores habitat information for each pixel. Information includes flooding frequency (these are categorised), hydrological event occurrence (from the hydrology module) rainfall periodicity (from the rainfall module), channel morphology, geomorphic units and substratum.

5.3.4 Initial Vegetation

A stochastic procedure generates initial vegetation before the model can be run. Individuals of the 4 key species are assigned to each 5x5 m grid based on the template qualities of that grid, the probabilities of occurrence of that class by species combination with those qualities, and the assumption that species do not coexist within a single 5x5 m grid. Colour coding of grids only distinguishes between terrestrial and riparian individuals, and not between different species. The stochastic nature of this procedure is due to the generation of a random number for each grid cell and a comparison between the random number value and the probability value for occurrence of that species by class by template quality combination.

5.4 GERMINATION MODULE

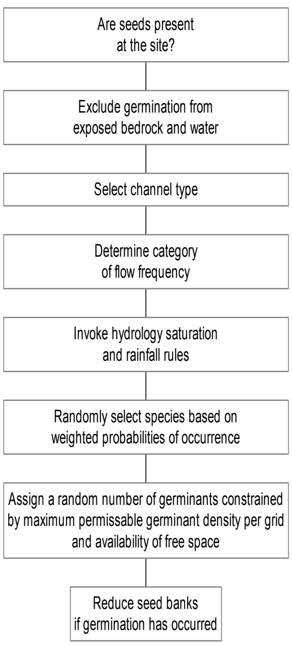

Figure 5.5 Development process of the germination module.

Seed availability at each grid is first determined (Figure 5.5). This information is obtained from the seed bank module (Figure 5.2). If no seeds are present at the grid, the germination module ends and moves to the next grid. If seeds are present, the germination module then gathers site information for that grid from the site module. Germination is excluded from exposed bedrock and permanent water in the active channel. Channel morphology and category of flow frequency are determined. Information is then gathered from the hydrology and rainfall modules. Hydrology saturation rules are accessed to determine the status of inundation of a grid based on its category of flow frequency and actual discharge values. Germination is excluded from inundated areas. Rainfall rules determine whether germination is possible at sites not affected by in-channel water at the time. One of the 4 key species is then randomly chosen to germinate at the site. Random choice is influenced by weighted, measured probabilities of occurrence of species by class combinations under defined site quality conditions. A random number of germinants of the selected species is introduced, but the actual number of germinants is constrained by density dependence (in the form of maximum permissible germinant density) and the availability of space. Once germination has occurred, relevant seed bank values for that grid are reduced.

5.5 GROWTH MODULE

This module starts by accessing information about hydrological states for the current year (Figure 5.6). It then calls the germination module in that year. Individuals grow on an annual time step, and the age determines the class of each individual. First, senescent adults become one year older if they survive. If individuals survive to the maximum age that is set in the model, death is automatic in the following year. Similarly, mature adults, young adults, saplings, seedlings and germinants all become one year older if they survive, or they move on to the next size class if they become old enough. The longevity of each size class is not hard-coded and may be permanently changed by users. Mortality is in accordance with measured values of survival, and is dependent on hydrological events (Table 5.1).

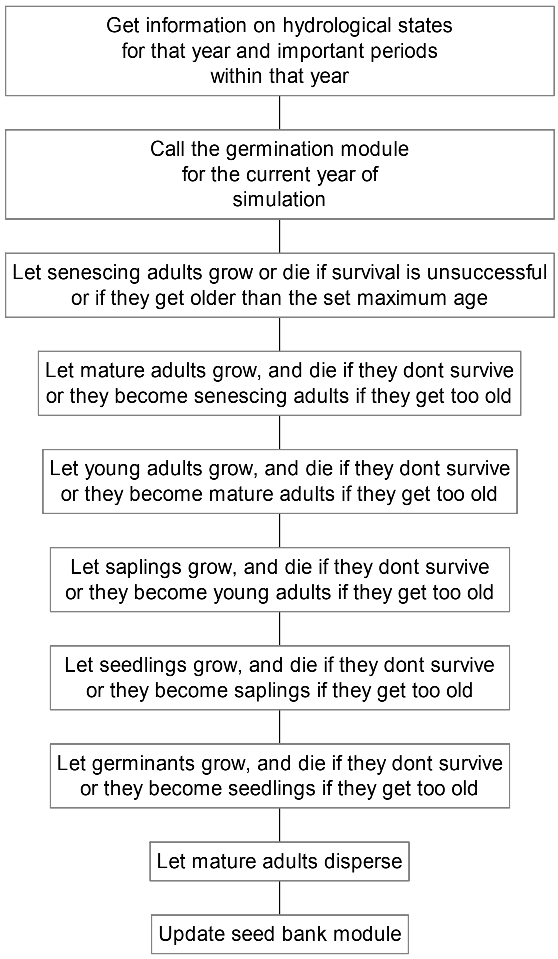

Figure 5.6 Development process of the growth module.

5.6 DISPERSAL MODULE

Only mature adults produce propagules which disperse, and dispersal is only significant to grid cells that are within 15 m (or 2 grid spaces) of the dispersing individual. These distances are based on germination data for riparian trees. The dispersal module inputs directly into the seed bank module which increases seed bank values if dispersal is successful.

5.7 SEED BANK MODULE

Each grid cell is allowed to accumulate a seed bank for all 4 species. Each year that dispersal occurs to a grid, the value of the seed bank increases. The amount of increase is dependent on the proximity of the grid cell to the dispersing individual. The closer the grid cell is to the dispersing individual the greater is the increase in seed bank value. Mortality of seeds in the seed bank occurs when seeds germinate, die when longevity is exceeded, or die due to hydrological disturbance. The seed bank value (SBV) is a relative, positive integer and is given by:

$$SBV_{t+1} = SBV_{t0} + D - G - Db - SBV_{t-long}$$

where D is dispersal, G is germination, Db is death due to hydrological disturbance and $SBV_{t\text{-}long}$ is the dispersal input *long* years previously where *long* is the max longevity of seeds per species.

5.8 BIOTIC INFLUENCES

Competition is considered in the form of density dependence. Density dependence operates by simply defining a maximum permissible density per grid cell per species per class.

5.9 ADJUSTABLE PARAMETERS

The following parameters are adjustable by users:

1. Probabilities of occurrence: per channel type per species per category of flow frequency (active, seasonal, or ephemeral) per size class

2. Survivorship: per species per category of flow frequency (active, seasonal, or ephemeral) for juveniles and adults for each of 9 hydrological states (Table 5.1)
3. Longevity: per species per size class
4. Density: per species per size class
5. Hydrological states (Table 5.1): 9 for each of 4 channel types
6. Seed bank longevity: for each species

5.10 ASSUMPTIONS

Model assumptions include:

1. Only 1 species can occupy any 5x5 m grid cell in the initial vegetation stage
2. Regeneration is not seed limited
3. Only propagules of mature adults disperse significantly
4. Dispersal occurs at the end of the growing season
5. Seeds dispersed into the water die or pass through the modeled site
6. Fire, herbivory and animal dispersal do not contribute significantly to vegetation processes within the riparian zone
7. None of the key species occur on exposed bedrock
8. Geomorphological change is less important for terrestrialisation than flow regimes.

5.11 RULES FOR THE MODEL

5.11.1 Hydrology

1. A no-flow event occurs if there was no recorded flow for 80% or more of the days in the given year
2. A drought occurs if 30% or more of daily flows in the given year are no-flows, or extreme low flows, or base flows, AND 20% or less of the flows are intermediate
3. Other hydrological events (catastrophic, large, small and very small floods, high, intermediate, base and extreme low flows) occur if the corresponding magnitude occurs once or more within the given year

5.11.2 Rainfall

1. A wet year is where 550 mm of rainfall or more occurs in the wet season (December to May)
2. A dry year is where 380 mm of rainfall or less occurs in the wet season (December to May)

5.11.3 Dispersal

1. Only mature adults disperse. Dispersal by other size classes is assumed to be zero or negligible
2. Dispersal from mature individuals is double in amount to cells in the immediate vicinity (5-10 m), than to cells farther away (10-15 m)

3. The seedbank value increases by the yearly input from mature adults, if they exist, and is decreased yearly by the input *longevity* years ago: where *longevity* is the time for which seeds in the seedbank remain viable

5.11.4 Seedbanks

1. Seedbanks are reduced by 1 level if germination occurs

5.11.5 Germination

1. Germination takes place if seeds are present in the seedbank, and rainfall occurs at least daily for 7 or more days
2. Germination also takes place on active features if seeds are present in the seedbank, and base flows occur in the growing season
3. Germination also takes place on seasonal features if seeds are present in the seedbank, and intermediate flows occur in the growing season
4. Germination also takes place on ephemeral features if seeds are present in the seedbank, and very small floods occur in the growing season
5. Germinants at a distance from the active channel die if no rainfall occurs for 21 or more consecutive days
6. Germination is density dependent, limited by a maximum number of germinants that can co-exist in a single cell

5.11.6 Growth

1. Survival of any individual is determined by a measured or estimated probability of survival, the actual value depending on the class of individual and the flow category at the site where that individual occurs

2. The class of the individual is determined by its age, and the age-class relationship is adjustable by the user

The Terrestrial Model, and the model code are available on CD from the Water Research Commission, or can be downloaded from the Internet at http://www.wits.ac.za/cwe/kruproj.htm#rbm.
The Breonadia Model, and the User Manual can also be downloaded from the Internet at http://www.wits.ac.za/cwe/kruproj.htm#rbm.

CHAPTER 6

ANALYSIS OF THE TERRESTRIALISATION MODEL OUTPUT

6.1 VALIDATION

We define validation as the process of assessing correspondence between the output and the rules applied in the model (Starfield *et al.*, 1990). Validation of the model proved to be an extremely important process for reconciling rules within the model and model output. This was achieved through isolating the outputs of key components of the model, namely, survival and growth, longevity, density dependence, seed bank longevity, dispersal and germination, and responses to hydrological states, and checking them against the respective rules applied in the model. ACRU (Schulze, 1995) simulated natural flow, including a no flow event and a catastrophic flood, was used as the hydrological input. In so doing, the effects of all possible hydrological events were validated against key components of the model.

In many instances, rules applied in the model were not operating correctly when scrutinized in greater detail. What appeared to be correct in the overall output was not always so when the outputs of the key components were isolated and checked in detail. In most cases this was due to errors in the coding of the model. The appropriate corrections were made to the coding of the model, so that at present all rules are correctly applied. The following are two examples of how rules were validated.

6.1.1 *Dichrostachys* Seedbank Example

The spatial accounting of the *D. cinerea* seed bank over 55 years is shown in Figure 6.1. Note the concentric decrease in a numeric measure of seed abundance around mature adult individuals, and the change in seed abundance at any given position through time. The rules for *D. cinerea* seed banks and dispersal state that seeds only remain viable for 8 years and that only mature adults disperse viable seed. The mature adult phase endures for 15 years if survival is successful. This means that at any given position along the river, when an individual becomes a mature adult, the seed bank should become established in that area, increase and be maintained over the next 15 years or until that individual dies or becomes a senescent adult, at which time the seed bank should steadily decline over 8 years and become non-existent in the absence of incoming mature adults or mature adults in close proximity to that position.

An example of this dynamic is illustrated by the circled areas from year 28 to 46 in Figure 6.1. A seedbank is initiated in year 29, increases, is maintained and then decreases over 18 years. The increase in year 48 is a result of an incoming mature adult that begins to add to the almost completely depleted seed bank. These outputs serve to validate the rules for *D. cinerea* dispersal and seed bank and mature adult longevity.

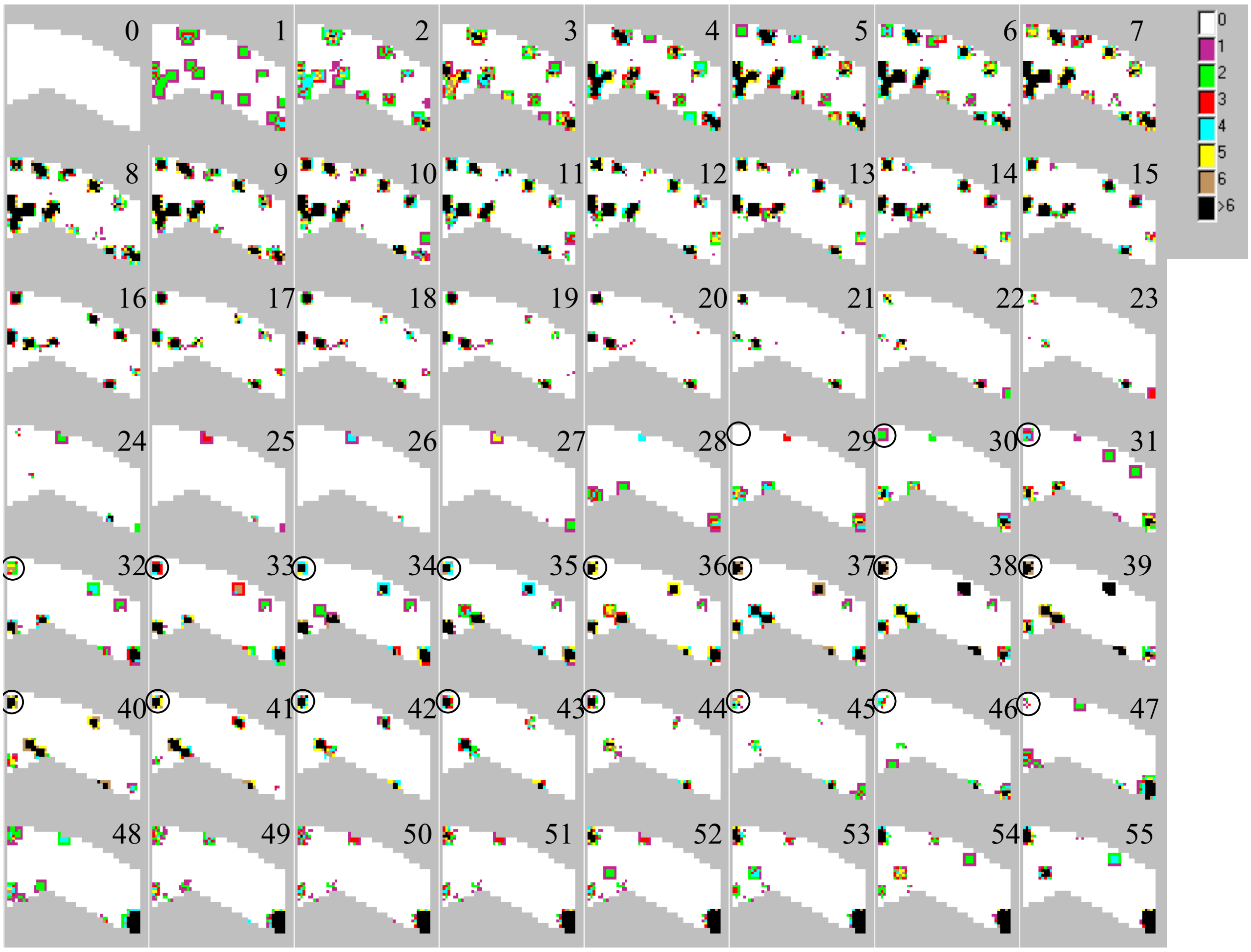

Figure 6.1 Model output of the status of the *Dichrostachys cinerea* seedbank over 55 years.

6.1.2 Catastrophic Flood and No-flow Examples

When a hydrological scenario that included a catastrophic flood in year 49 and a no-flow event in year 21 was loaded, the model registered the presence of both events in the hydrological time series and a summary of hydrological events and rainfall (Figure 6.2). These outputs validate the rules for hydrological state (event) recognition and calculation.

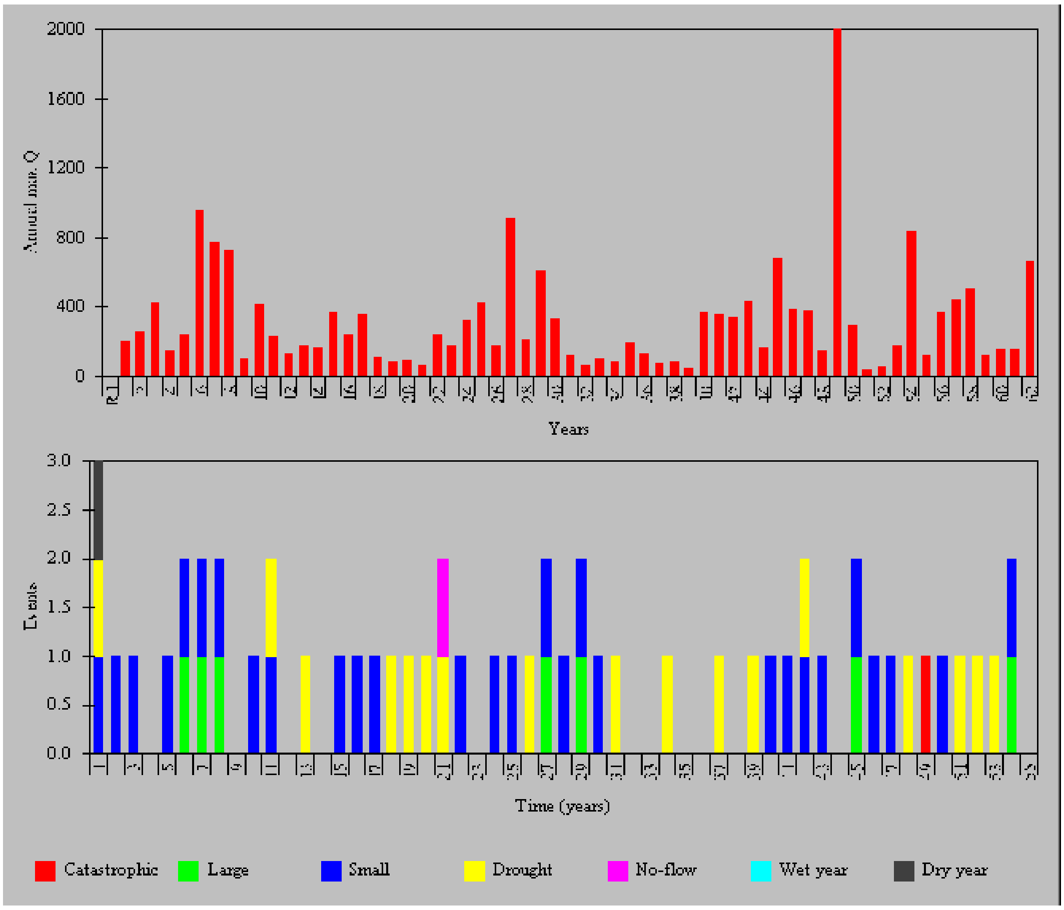

Figure 6.2 Yearly maximum discharge over 55 years (top) and hydrological and rainfall summary for the same period (bottom) for a hydrological scenario containing a no-flow event in year 21 and a catastrophic flood in year 49.

The population response to this scenario shows clear reductions in both terrestrial and riparian numbers in both years 21 and 49 (Figure 6.3). This to be expected since both have low survivorship when no-flow events or catastrophic floods occur. The response also serves to validate the correct use of survival probabilities for different hydrological events.

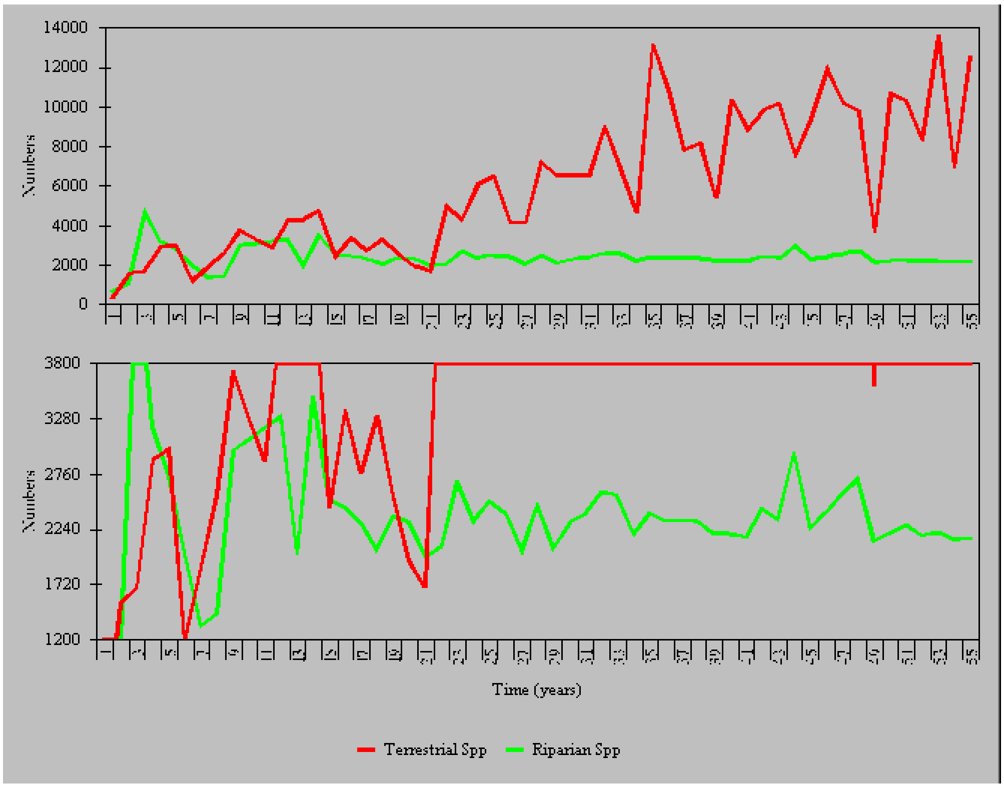

Figure 6.3 Numbers of terrestrial and riparian species over 55 years in response to a hydrological scenario with a no-flow event in year 21 and a catastrophic flood in year 49. Y-axis scale has been reduced in the lower graph for improved resolution in years 21 and 49.

6.2 SENSITIVITY ANALYSIS

Parameter values are a source of uncertainty in biological modelling, (O'Neil and Gardner, 1979) as the mean or variance of the population from which the parameters are taken is not always known. Uncertainty in parameter values will affect model predictions, but the effect can be investigated using parameter sensitivity analyses (Haefner, 1996).

6.2.1 Parameter Sensitivity

In a sensitivity analysis, parameters are systematically changed to determine their effect on the output (Starfield and Bleloch, 1991). The model is first run with its set of default parameters and its output is used as a benchmark against which all other runs are measured. Single or multiple parameter analyses can be performed (Haefner, 1996). In single parameter analyses, each of the parameters is changed one at a time, either uniformly or variably to determine the effect on model output. In multiple parameter analyses more than one variable is altered to assess interactions between variables. If the model is linear and deterministic, then single parameter sensitivity analyses are often sufficient (Starfield and Bleloch, 1991). If parameters are changed uniformly, all parameters are changed by the same percentage of their respective nominal values. The variable approach weights the altered interval of each parameter by the variance of the estimate of that parameter (if this is known) (Haefner, 1996).

We used a single parameter sensitivity analyses, and altered nominal parameters uniformly by adding and subtracting as close to 30 % of the original value as possible. It was not always possible to use these factors for all parameters. For example, a nominal survival probability of 0.967 cannot be meaningfully increased by 30 %, so its value increase was set to 1.

The sensitivity index (S) derived from changes in the model output was used to compare the relative sensitivity of all parameters. S compares the change in model output to model response for a nominal set of parameters (Haefner, 1996). S is therefore the ratio of standardized change in response (model output) to standardized change in parameter values, and is given by:

$$S = \frac{\frac{R_a - R_n}{R_n}}{\frac{P_a - P_n}{P_n}}$$

where R_a and R_n are model output responses for altered and nominal parameters respectively, and P_a and P_n are the altered and nominal parameters respectively. The absolute value of S was used to make comparisons because parameters could then be ranked according to their S-values. Negative and positive values indicated the same level of sensitivity (e.g., an S-value of 0.379 and -0.379), but indicate a positive or negative response to changes respectively.

The following parameters were used in the sensitivity analyses, which resulted in over 850 model runs of 20 years each:

- Survival of juveniles and adults of each species on actively, seasonally and ephemerally flooded features for each hydrological state
- Longevity of size classes for each species
- Density dependence
- Hydrological state definition
- Seed bank longevity for each species

6.2.2 Results

On average, juveniles were more sensitive than adults and riparian species were more sensitive than terrestrial species, but the maximum sensitivity was sometimes higher in adults than in juveniles and the T:R ratio was mostly more sensitive than both terrestrial and riparian species (Table 6.1). *Acacia nigrescens* was the least sensitive species whereas *S. guineense* was the most sensitive (particularly juveniles).

Table 6.1 Mean (with se of the mean) and maximum S-values for combinations of species and size classes.

		Mean	Maximum	Std Error of Mean
All Species	T:R ratio	1.41	9.43	0.054
	All size classes	0.51	4.17	0.023
	Juveniles	27.41	526.06	3.762
	Adults	0.56	5.48	0.033
Terrestrial Species	All size classes	0.71	5.18	0.033
	Juveniles	0.90	7.15	0.042
	Adults	0.47	8.83	0.040
Riparian Species	All size classes	0.97	6.35	0.052
	Juveniles	1.80	16.51	0.104
	Adults	0.83	5.90	0.041
Acacia nigrescens	All size classes	0.55	4.39	0.035
	Juveniles	0.81	7.03	0.049
	Adults	0.41	3.59	0.026
Dichrostachys cinerea	All size classes	1.40	8.24	0.063
	Juveniles	1.72	10.12	0.076
	Adults	0.95	15.45	0.073
Combretum erythrophyllum	All size classes	1.37	11.15	0.053
	Juveniles	1.80	16.61	0.103
	Adults	0.82	7.68	0.042
Syzygium guineense	All size classes	1.67	10.74	0.052
	Juveniles	6.76	319.87	2.358
	Adults	1.67	10.62	0.046

Terrestrial:Riparian Ratio

The Terrestrial:Riparian (T:R) ratio was most sensitive to increased juvenile and adult survival of all species when no hydrological events, small floods and droughts occurred. This was particularly true where increases ensured 100% survival (Table 6.2). Most of the changes in survival applied to riparian species, indicating that the T:R ratio is more sensitive to changes in riparian survival than terrestrial survival, and in all cases sensitivity indicated a negative response, meaning the T:R ratio decreased, which is desirable. Ratios were also highly sensitive to an increased probability of catastrophic floods.

Table 6.2 Sensitivity (S-value) of T:R ratios and corresponding variable changes resulting in highest sensitivities.

Variable Change	S-value
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	-9.4
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	-9.0
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	-8.6
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	-7.5
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	-6.5
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Small flood)	-5.9
+ Sygu adult survival (seasonal) from 0.95 to 1.0 (Default)	-5.6
+ Sygu adult survival (ephemeral) from 0.95 to 1.0 (Default)	-5.2
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	-5.1
- large floods and + catastrophic floods	-5.0

Where: Acni = *Acacia nigrescens,* Dici = *Dichrostachys cinerea*
Coer = *Combretum erythrophyllum,* Sygu = *Syzygium guineense*
+ denotes an increase, - denotes a decrease
Default is when no defined hydrological event has occurred

Sensitivity was highest when survival was set at 100%, so we excluded these values to determine whether other variable changes resulted in high sensitivity values (Table 6.3). With these exclusions, the T:R ratio was most sensitive to an increased probability of catastrophic floods, changes in *C. erythrophyllum* and *D. cinerea* longevity, and changes in *S. guineense* and *D. cinerea* survival (particularly changes to adult survival for *D. cinerea*) when droughts, small floods or no-flow events occurred.

Table 6.3 Sensitivity (S-value) of T:R ratios and corresponding variable changes resulting in highest sensitivities excluding those changes to survival probabilities of 1.0. Details are as in Table 6.2.

Variable Change	S-value
- large floods and + catastrophic floods	-5.0
- Coer Sapling longevity from 4 to 3	3.0
+ Sygu adult survival (seasonal) from 0.3 to 0.375 (No-Flow)	-2.5
+ Dici adult survival (seasonal) from 0.01 to 0.0125 (Drought)	-2.5
- Dici Senescent adult longevity from 5 to 4	2.5
- Dici juvenile survival (seasonal) from 0.001 to 0.00075 (Drought)	2.4
- Dici adult survival (ephemeral) from 0.8 to 0.6 (Small flood)	2.4
+ Dici Senescent adult longevity from 5 to 6	-2.4
- Dici adult survival (ephemeral) from 0.95 to 0.7125 (Default)	2.4
+ Dici juvenile survival (active) from 0.01 to 0.0125 (Small flood)	-2.3

Combined Population Response

A combined population response of all species was most sensitive to increased survival to 100% (a positive response), decreased base flows and increased catastrophic floods (Table 6.4). Combined population response was more sensitive to changes in size class longevity than was the T:R ratio, particularly *A. nigrescens* juvenile longevity.

Table 6.4 Sensitivity (S-value) of all species and size classes combined, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	4.2
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	3.9
- Acni sapling longevity from 6 to 4	-3.8
+ Coer adult survival (ephemeral) from 0.9 to 1.0 (Small flood)	3.5
- Acni seedling longevity from 3 to 2	-3.4
+ Acni germinant longevity from 2 to 3	2.8
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	2.8
- base flows and + intermediate flows	-2.6
- Acni germinant longevity from 2 to 1	-2.2
- large floods and + catastrophic floods	2.2

An assessment of juvenile sensitivity indicated that juvenile population response is 100 fold more sensitive than either the T:R ratio or adults (compare Tables 6.5, 6.2 and 6.6). Juveniles of all species were most sensitive to increased survival, mostly of juvenile size classes during droughts and large or catastrophic floods (Table 6.5). Changes in survival were almost always for terrestrial species, and on features where those particular species did not usually occur.

Table 6.5 Sensitivity (S-value) of juveniles of all species combined, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Acni adult survival (active) from 0.001 to 0.00125 (Default)	526.1
+ Acni juvenile survival (seasonal) from 0.001 to 0.00125 (Drought)	511.8
+ Acni juvenile survival (seasonal) from 0.001 to 0.00125 (Large flood)	462.0
+ Dici juvenile survival (active) from 0.001 to 0.00125 (Default)	406.6
+ Dici adult survival (active) from 0.001 to 0.00125 (Drought)	380.0
+ Dici juvenile survival (seasonal) from 0.001 to 0.00125 (Large flood)	362.3
+ Acni juvenile survival (active) from 0 to 0.001 (Large flood)	328.0
+ Coer juvenile survival (ephemeral) from 0.001 to 0.00125 (Default)	271.3
+ Dici juvenile survival (seasonal) from 0 to 0.001 (Catastrophic flood)	228.9
+ Sygu juvenile survival (ephemeral) from 0.001 to 0.00125 (Drought)	223.5

Adults of all species were most sensitive to changes in *A. nigrescens* juvenile longevity, and increased survival (particularly adults) (Table 6.6). *Acacia nigrescens* contributes to adult sensitivity in the model more than any of the other species, but is itself the least sensitive.

Table 6.6 Sensitivity (S-value) of adults of all species combined, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
- Acni sapling longevity from 6 to 4	-5.5
- Acni seedling longevity from 3 to 2	-5.3
+ Acni germinant longevity from 2 to 3	4.3
+ Coer adult survival (ephemeral) from 0.9 to 1.0 (Small flood)	4.0
- Acni germinant longevity from 2 to 1	-3.6
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	3.6
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	2.7
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	2.5
+ Acni adult survival (ephemeral) from 0.95 to 1.0 (Default)	2.4
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	2.4

Population Response of Terrestrial Species

All size classes of the terrestrial species combined were most sensitive to increased survival (to 100%) of riparian species, and to altered juvenile longevity in *A. nigrescens* (Table 6.7). When variable changes that resulted in 100% survival were excluded, sensitivity was highest when *A. nigrescens* juvenile longevity was changed, when fewer small floods occurred, and when survival of terrestrial species was changed, mostly during small floods (Table 6.7). Removal of germinants from analyses made no significant difference to sensitivity (a combined response of both terrestrial species and all classes was significantly correlated to a response where germinants had been removed: r^2=0.999, DF=381).

Table 6.7 Sensitivity (S-value) of all terrestrial species and size classes combined, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2

Variable Change	S-value
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	-5.2
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	-4.6
- Acni seedling longevity from 3 to 2	-3.2
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	-3.0
- Acni sapling longevity from 6 to 4	-2.8
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	-2.8
+ Acni germinant longevity from 2 to 3	2.6
+ Coer juvenile survival (active) from 0.9 to 1.0 (Default)	-2.5
+ Dici adult survival (ephemeral) from 0.95 to 1.0 (Drought)	-2.4
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	-2.4
Variable Changes excluding those to 100 % survival	
- Acni seedling longevity from 3 to 2	-3.2
- Acni sapling longevity from 6 to 4	-2.8
+ Acni germinant longevity from 2 to 3	2.6
+ very small floods and - small floods	2.1
- Dici adult survival (ephemeral) from 0.8 to 0.6 (Small flood)	1.9
- Acni germinant longevity from 2 to 1	-1.9
- Acni adult survival (ephemeral) from 0.8 to 0.6 (Small flood)	1.8
- Dici adult survival (ephemeral) from 0.95 to 0.7125 (Default)	1.7
+ Dici juvenile survival (seasonal) from 0.01 to 0.0125 (Small flood)	-1.7
- Coer Sapling longevity from 4 to 3	1.6

Terrestrial juveniles were most sensitive to increased survival of both juveniles and adults, especially where changes resulted in 100% survival when no defined hydrological events occurred (Table 6.8).

Table 6.8 Sensitivity (S-value) of terrestrial species juveniles, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	-7.2
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	-6.3
+ Dici adult survival (ephemeral) from 0.95 to 1.0 (Drought)	-4.0
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	-4.0
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	-3.8
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	-3.6
+ Coer juvenile survival (active) from 0.9 to 1.0 (Default)	-3.5
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Small flood)	-3.4
+ Acni adult survival (ephemeral) from 0.95 to 1.0 (Default)	-2.8
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	-2.8

Terrestrial adults were most sensitive to changes in juvenile *A. nigrescens* longevity, increased survival of riparian species and more large floods (Table 6.9).

Table 6.9 Sensitivity (S-value) of terrestrial adults, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
- Acni seedling longevity from 3 to 2	-8.8
- Acni sapling longevity from 6 to 4	-7.8
+ Acni germinant longevity from 2 to 3	6.3
- Acni germinant longevity from 2 to 1	-5.7
+ Sygu adult survival (ephemeral) from 0.95 to 1.0 (Default)	-2.2
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	-2.0
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	-1.8
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	-1.6
+ Sygu adult survival (seasonal) from 0.95 to 1.0 (Default)	-1.6
- small floods and + large floods	1.5

Population Response of Riparian Species

Combined size classes of riparian species were most sensitive to increased survival (to 100%) of predominantly riparian species (Table 6.10). When variable changes that resulted in 100% survival were excluded, sensitivity was highest when *A. nigrescens* and *C. erythrophyllum* juvenile longevity was changed, and when decreased survival of adult terrestrial species occurred, mostly during small floods (Table 6.10). Removal of germinants from analyses made a difference to sensitivity (r^2=0.477, DF=381). Sensitivity as a result of changes to juvenile *A. nigrescens* longevity increased when germinants were not considered.

Table 6.10 Sensitivity (S-value) of all riparian species and size classes combined, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	-6.4
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	-5.8
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	-4.4
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	-4.2
+ Dici adult survival (ephemeral) from 0.95 to 1.0 (Drought)	-3.8
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	-3.8
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Small flood)	-3.6
+ Coer adult survival (active) from 0.95 to 1.0 (Default)	-3.6
+ Sygu adult survival (seasonal) from 0.95 to 1.0 (Default)	-3.5
+ Sygu adult survival (ephemeral) from 0.95 to 1.0 (Default)	-3.4
Variable Changes excluding those to 100 % survival	
- Acni seedling longevity from 3 to 2	-2.7
- Acni sapling longevity from 6 to 4	-2.3
+ Acni germinant longevity from 2 to 3	2.2
- Dici adult survival (ephemeral) from 0.8 to 0.6 (Small flood)	2.1
- Acni adult survival (ephemeral) from 0.8 to 0.6 (Small flood)	2.0
- Dici adult survival (ephemeral) from 0.95 to 0.7125 (Default)	1.9
+ Dici juvenile survival (seasonal) from 0.01 to 0.0125 (Small flood)	-1.9
- Coer Sapling longevity from 4 to 3	1.8
- Acni adult survival (active) from 0.01 to 0.0075 (Small flood)	1.8
- Dici adult survival (ephemeral) from 0.7 to 0.525 (Large flood)	1.8

Riparian juveniles were most sensitive to increased survival of riparian species (mostly when no hydrological event occurred), decreased probabilities of base flows occurring, decreased longevity of *C. erythrophyllum* juveniles, and increased seed bank longevity of *D. cinerea* (Table 6.11).

Table 6.11 Sensitivity (S-value) of riparian juveniles, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	16.5
- base flows and + intermediate flows	-14.3
- Coer Sapling longevity from 4 to 3	-12.1
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	11.8
+ Coer adult survival (seasonal) from 0.8 to 1.0 (Drought)	9.6
+ Coer juvenile survival (seasonal) from 0.5 to 0.625 (Small flood)	9.4
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	7.5
+ Coer adult survival (active) from 0.95 to 1.0 (Default)	-7.2
+ Coer juvenile survival (seasonal) from 0.95 to 1.0 (Default)	7.2
+ dici seed bank longevity	6.8

Riparian adults were most sensitive to increased survival of mostly riparian species, and to changes in *A. nigrescens* sapling longevity (Table 6.12).

Table 6.12. Sensitivity (S-value) of riparian adults, and corresponding variable changes resulting in highest sensitivities. Details are as in Table 6.2.

Variable Change	S-value
+ Coer adult survival (ephemeral) from 0.95 to 1.0 (Default)	5.9
+ Coer adult survival (ephemeral) from 0.9 to 1.0 (Small flood)	5.9
- Acni sapling longevity from 6 to 4	-4.5
+ Sygu adult survival (ephemeral) from 0.95 to 1.0 (Default)	4.3
+ Sygu adult survival (active) from 0.95 to 1.0 (Default)	4.1
+ Coer adult survival (seasonal) from 0.95 to 1.0 (Default)	4.0
- Acni seedling longevity from 3 to 2	-3.9
+ Acni juvenile survival (ephemeral) from 0.95 to 1.0 (Default)	3.8
+ Acni adult survival (ephemeral) from 0.95 to 1.0 (Default)	3.7
+ Coer adult survival (active) from 0.95 to 1.0 (Default)	3.6
+ Sygu adult survival (seasonal) from 0.95 to 1.0 (Default)	3.5
+ Sygu juvenile survival (active) from 0.95 to 1.0 (Default)	3.5

6.2.3 Implications of results

Results of sensitivity analyses demonstrate that the model is driven primarily by hydrologically determined survival and longevity. Not only does this make the Terrestrialisation Model a scenario evaluation tool, but it also indicates that research and monitoring efforts should be focussed on providing accurate estimates for survival of different size classes when exposed to defined hydrological events, and longevity of different size classes for all species.

6.3 EVALUATING SCENARIOS

The Terrestrialisation Model was used to run three different hydrological scenarios to compare their effects on population response and terrestrialisation of a selected section of riparian zone along the Sabie River. Each scenario was tested in a pool-rapid channel and the model was run for 60 years. Hydrological output from the ACRU model (Schulze, 1995) was used as a "natural" scenario (Figure 6.4), and a 1% increase or decrease of daily ACRU discharge comprised scenarios of progressive increased (wetting scenario; Figure 6.5) and reduced (drying scenario; Figure 6.6) flows respectively.

6.3.1 "Natural" Scenario

The spatial population output by year 60 showed an almost even mix of riparian and terrestrial individuals (Figure 6.4A). A time series of the population response of terrestrial and riparian species revealed riparian dominance for the first 30 years however, after which time terrestrial species were frequently more abundant (Figure 6.4B). Consequently, there was a general increase in the T:R ratio over the 60 year period, although its value never exceeded 1.6 (Figure 6.4C). The total T:R ratio (for all geomorphic features) was largely explained by the ratio on ephemerally flooded features only (Compare Figures 6.4 C and D).

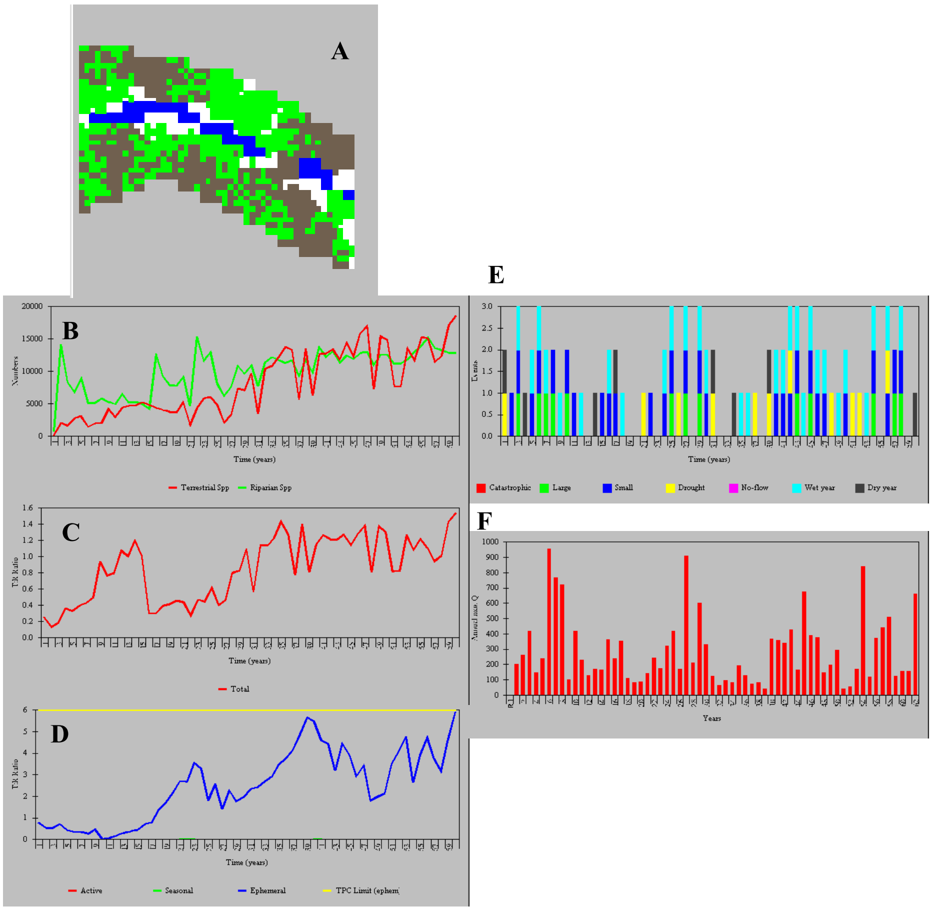

Figure 6.4. Simulated population response to a “natural” scenario using ACRU data. Spatial population output in year 60 (A); Population time series over 60 years (B); T:R ratio time series over 60 years for all features (C) and for ephemeral features (D); Hydrological and rainfall summary (E); and annual maximum discharge (F).

6.3.2 Drying Scenario

The spatial population output in year 60 showed a predominance of terrestrial individuals (Figure 6.5A). A time series of the population response of terrestrial and riparian species revealed frequent riparian dominance however, and lower numbers of both terrestrial and riparian species than the “natural” scenario (Figure 6.5B). There was a general increase in the T:R ratio over the 60 year period, especially on ephemerally flooded features where the ratio almost reached 25 (Compare Figures 6.5 C and D).

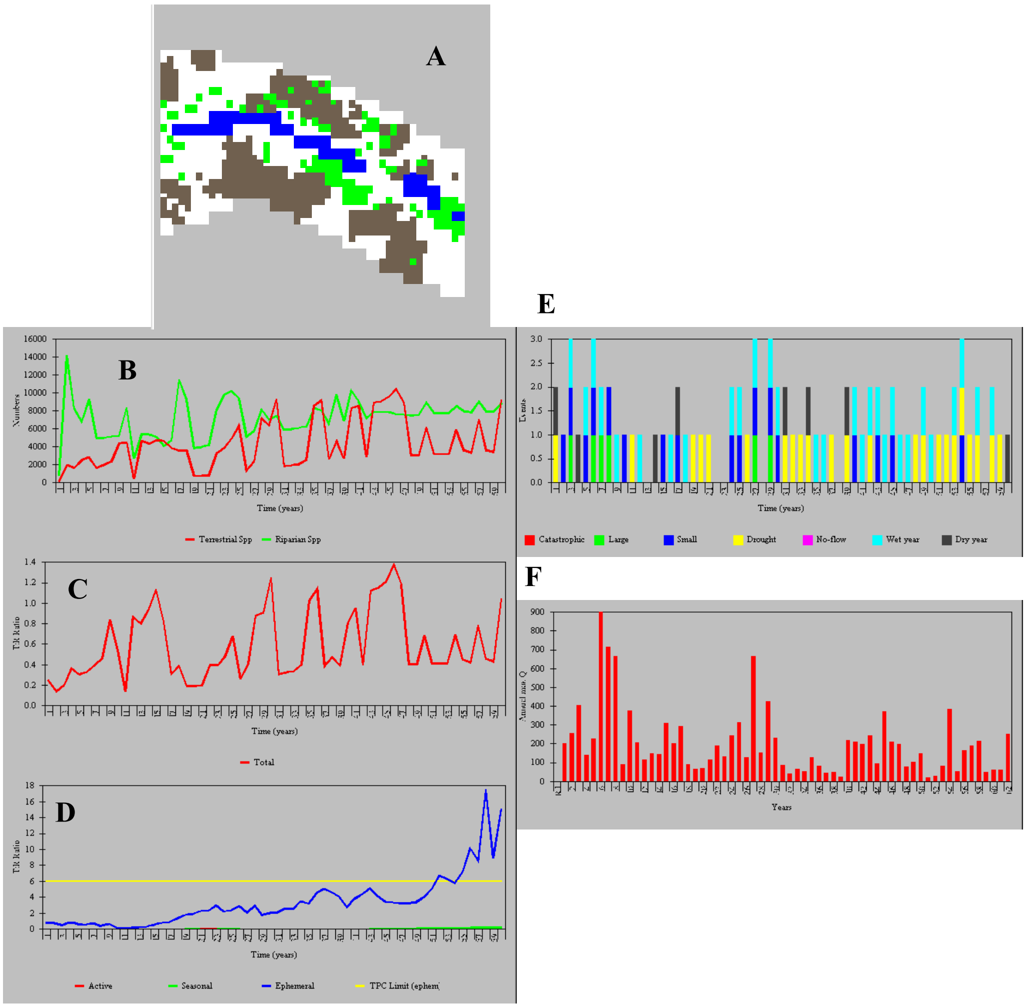

Figure 6.5 Simulated population response to a drying scenario using ACRU data reduced by 1% per year. Spatial population output in year 60 (A); Population time series over 60 years (B); T:R ratio time series over 60 years for all features (C) and for ephemeral features (D); Hydrological and rainfall summary (E); and annual maximum discharge (F).

6.3.3 Wetting Scenario

The spatial population output in year 60 showed a marked predominance of riparian individuals (Figure 6.6A). A time series of the population response of terrestrial and riparian species revealed riparian dominance for almost the entire 60 years, a trend which increased with time (Figure 6.6B). Consequently, there was a general decrease in the T:R ratio over the 60 year period, even on ephemerally flooded features (Compare Figures 6.6 C and D).

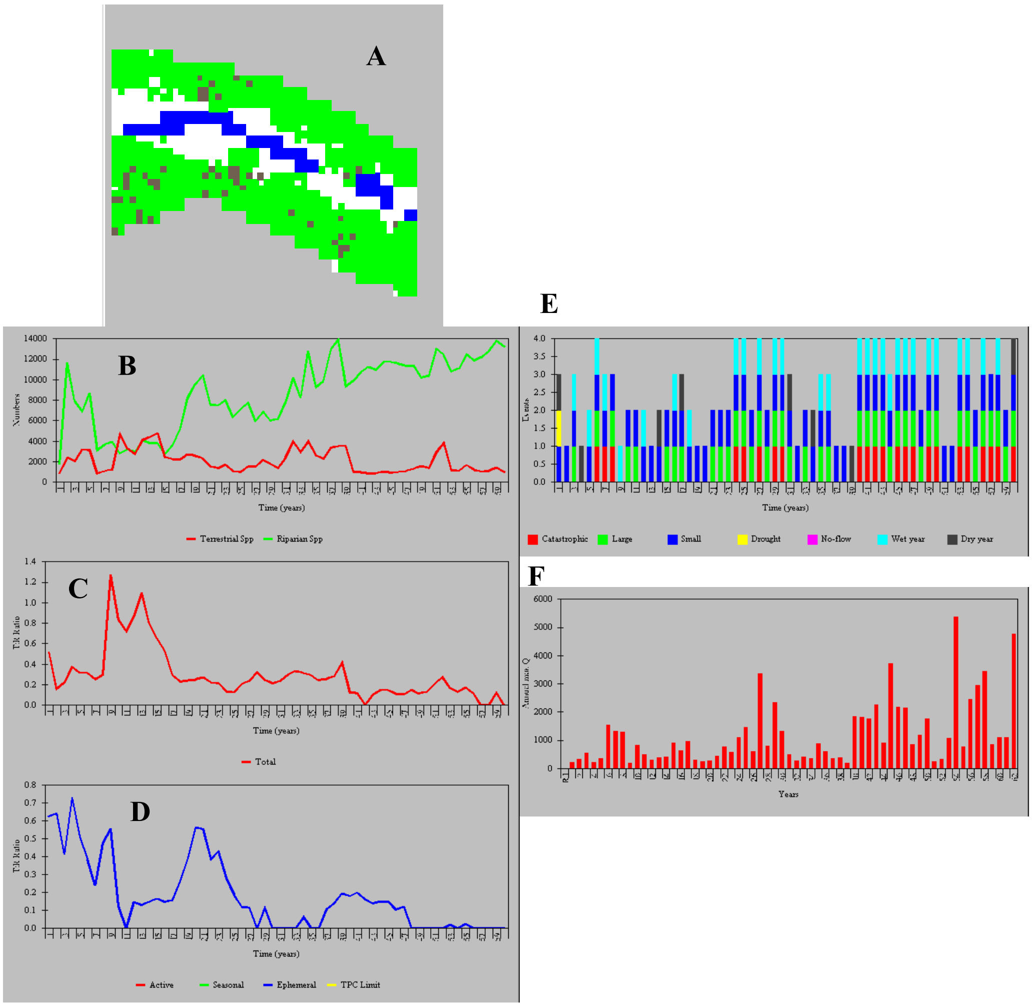

Figure 6.6 Simulated population response to a wetting scenario using ACRU data increased by 1% per year. Spatial population output in year 60 (A); Population time series over 60 years (B); T:R ratio time series over 60 years for all features (C) and for ephemeral features (D); Hydrological and rainfall summary (E); and annual maximum discharge (F).

6.4 SETTING AND EVALUATING THE TPC

At the outset of this project, 4 key species were selected to work on; 2 riparian and 2 terrestrial. These four species occur over the full range of features on the macro-channel floor, but have distinctly different optima of where they occur. This means that the total T:R ratio (total referring to a ratio incorporating active, seasonal and ephemeral features) will lack resolution and always underestimate the problem of terrestrialisation since it most markedly occurs on ephemeral features, and especially the macro-channel bank. A low T:R ratio may therefore occur due to high numbers of riparian individuals on active and seasonal features, whereas high numbers of terrestrial individuals occur on ephemeral features, effectively masking the problem of terrestrialisation on ephemeral features.

For this reason we have determined to set the TPC (in the form of T:R ratio limits) separately for active, seasonal and ephemeral features so that the TPC audit is conducted along a categorised flow frequency gradient. In this way the problem of terrestrialisation, if it exists or comes into being, can be monitored in reasonable detail. We have also determined to set the TPC for adult populations only. This is due to high volatility and low survival in the numbers of juveniles which makes using them to monitor trends more risky than using the more stable adult populations.

It is apparent from the scenario evaluation (Section 6.3) that on ephemeral features where terrestrialisation is most problematic, the T:R ratio declines during wetter periods and increases during dryer periods. It follows that the oscillation and pattern of wet and dry periods will determine whether the ratio increases or decreases indefinitely, or is dynamic about some check level.

In response to a “natural” scenario, the T:R ratio reaches a maximum of 6 at the end of a period of 60 years (Figure 6.4D), whereas the ratio never goes as high as 0.8 in the wetting scenario, and continues to decline over the 60 years (Figure 6.6D). In response to the drying scenario the T:R ratio gradually increases over the first 50 years, after which the increase becomes more rapid (Figure 6.5D). This exponential increase phase begins at a T:R ratio of about 6. However, the measured T:R range for ephemeral features was 8 to 11 from 2000 to 2002.

Using the drying scenario and at a T:R ratio of 6 (predicted value), the TPC would be exceeded by year 51, whereas at a ratio of 8 (measured value) the TPC would be exceeded by year 55 (Figure 6.5D). That is only 4 unnoticed years of terrestrialisation if a ratio of 8 rather than 6 were used as the TPC for ephemeral features. This difference of 4 years, as well as the point at which exponential increase in the T:R ratio on ephemeral features occurs, was additionally tested in two more drying scenarios: one where ACRU flow data (Schulze, 1995) were reduced by 1.5% per year, and the other similarly by 2%.

In response to the 1.5% drying scenario the T:R ratio reached 6 by year 50 and 8 by year 51, the difference being 3 years less than in response to the 1% drying scenario. By comparison to the 1% drying scenario, a T:R ratio of 6 also marked the exponential increase phase, but one year after it began, and while the increasing trend over 60 years was similar, a limit of 6 was reached 1 year earlier.

In response to the 2 % drying scenario the T:R ratio reached 6 and 8 by year 41, the difference of 0 being 4 and 3 years less than in response to the 1% and 1.5% drying scenarios respectively. By comparison to the 1% and 1.5% drying scenarios, a T:R ratio of 6 marked the exponential increase phase less well, and while the increasing trend over 60 years was similar, a limit of 6 was respectively reached 10 and 9 years earlier.

We took these modelled results as justification for the choice of 6 as the TPC (T:R ratio limit) on ephemerally flooded features, erring on the conservative side. It must also be clearly stated that this TPC is a first estimate, which must be refined and changed if necessary by the SAM process through which it will operate.

Setting limits for the TPC on actively and seasonally flooded features was more difficult because the numbers of terrestrial individuals was often too low to calculate a T:R ratio (we used a cut-off of 10 individuals below which a ratio becomes deceiving). The maximum T:R ratio predicted on seasonally flooded features was 0.7, whereas none was available for actively flooded features. For this reason we decided to use only measured T:R ratios to set as limits, and suggest T:R ratio limits of 0.2 and 1 for active and seasonal features respectively. It must again be emphasised however that these are first estimates that will also need refinement through the SAM process.

CHAPTER 7

MONITORING TO AUDIT MANAGEMENT GOALS AND REFINE THE MODELS

Monitoring is a long term and ongoing operation, and a component of the present study was to implement monitoring programmes for both the *Breonadia* Model (Section 7.1) and for the Terrestrialisation Model (Section 7.2). The *Breonadia* Model was developed prior to the start of the present study (MacKenzie *et al.*, 1999), and monitoring data was collected annually for the duration of this study. The results of the first three years of monitoring to validate and refine the *Breonadia* Model are presented in Section 7.1.2. The results of the data collection for the Terrestrial Model (Chapter 4) highlighted where terrestrialisation posed the greatest threat, and monitoring sites were thus established in these areas (Section 7.2.2).

7.1 *BREONADIA* MODEL

7.1.1 Monitoring plan for the *Breonadia* model

Strategic adaptive management should incorporate a monitoring programme that provides a verification of the definition of the problem, and the appropriateness of the solution (Rogers and Biggs, 1999). Monitoring should be used to test the hypotheses on which adaptive management is based (Rogers and Biggs, 1999), and can be used to audit the goals or TPCs. A critical role of monitoring is the collection of data for model refinement and improvement of its predictive capability, as well as to generate scenarios of change trajectories.

The TPC for the loss of bedrock influence is that *B. salicina* displays a negative J-shaped curve in its population size structure for all non-germinant established individuals, in the rapid sections of pool-rapid channels (MacKenzie *et al.*, 1999). Five monitoring sites were thus identified and demarcated in various rapid sections in pool-rapid channels. However, these sections of river were seriously affected by the February 2000 floods, and there were few living *B. salicina* individuals remaining in these areas. An additional four monitoring sites were therefore placed in bedrock anastomosing channels, as these areas had healthier *B. salicina* populations. All the sites were permanently marked so that monitoring can be continued by KNP staff.

Monitoring began in August 2000, and was repeated in 2001 and 2002 (Table 7.1). Within the sites, every individual was recorded, and its stage class was noted. Stage classes were germinants (individuals with cotyledons), seedlings, saplings, young adults (individuals which are old enough to begin flowering), mature adults (individuals which are able to produce abundant flowers) and senescent adults (individuals which are no longer able to flower to their full extent). Many individuals were damaged by the flood, but were coppicing successfully. However, this led to problems with classification between the sapling, young adult, and mature adult stage classes. In many cases, individuals were so severely damaged that it was extremely difficult to determine in which stage class they had been prior to the flood.

7.1.2 Results of *Breonadia* monitoring

In both bedrock anastomosing and pool-rapid channels the population structure was opposite of a negative-J curve (Figure 7.1). This was due to the effect of the 2000 floods, which removed the majority of juveniles. The *Breonadia* TPC was thus exceeded, as predicted by the model when a "catastrophic" flood occurs (MacKenzie *et al.*, 1999).

No germinants were recorded in any year, in either channel type (Figure 7.1). This was due to the fact that the flood removed existing germinants, and the remaining adults were damaged to the extent that no flowering or seed dispersal occurred. No long-lived seed bank exists for this species, so recruitment can only occur once adults have recovered sufficiently to disperse seeds. Seedlings and saplings were only observed in bedrock anastomosing channels.

Greater numbers of adults (both young and mature) were recorded in bedrock anastomosing than in pool-rapid channels. Due to the fact that many individuals were severely damaged by the flood and were thus difficult to classify, it appears that a greater number of mature adults were recorded in bedrock anastomosing channels in 2001 than were recorded in 2000 (Figure 7.1). However, this is a result of classification problems, and is not due to an increase in numbers. No senescent adults survived the flood.

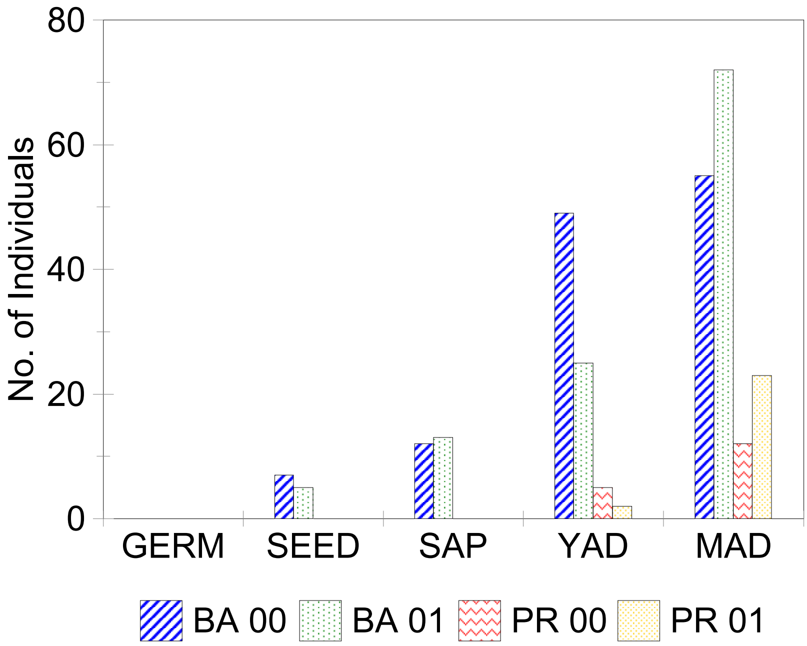

Figure 7.1 The number of *Breonadia salicina* individuals recorded in bedrock anastomosing (BA) and pool-rapid (PR) channels for years 2000 and 2001. GERM: germinants; SEED: seedlings; SAP: saplings; YAD: young adults; MAD: mature adults.

The results of two years of monitoring revealed that *Breonadia* populations in pool-rapid channels were severely damaged by the flood, and would take more than two years to recover. Populations within bedrock anastomosing sections, however, were less seriously affected, and would probably be able to recover more rapidly. We therefore decided to use only the bedrock anastomosing sites as permanent monitoring sites. In 2002, data were only collected from these sites (Figure 7.2).

The number of seedlings and saplings changed little between 2001 and 2002 in bedrock anastomosing channels (Figure 7.2). However, the number of both young and mature adults decreased. When the two adult age classes were combined, the abundance declined by 50% during the 2 years following the flood (from 104 to 51 individuals). The greater reduction in number between 2001 and 2002 (compared to between 2000 and 2001) is probably the result of individuals, after having survived the flood, dying at a later stage due to prolonged inundation, or prolonged post flood stress.

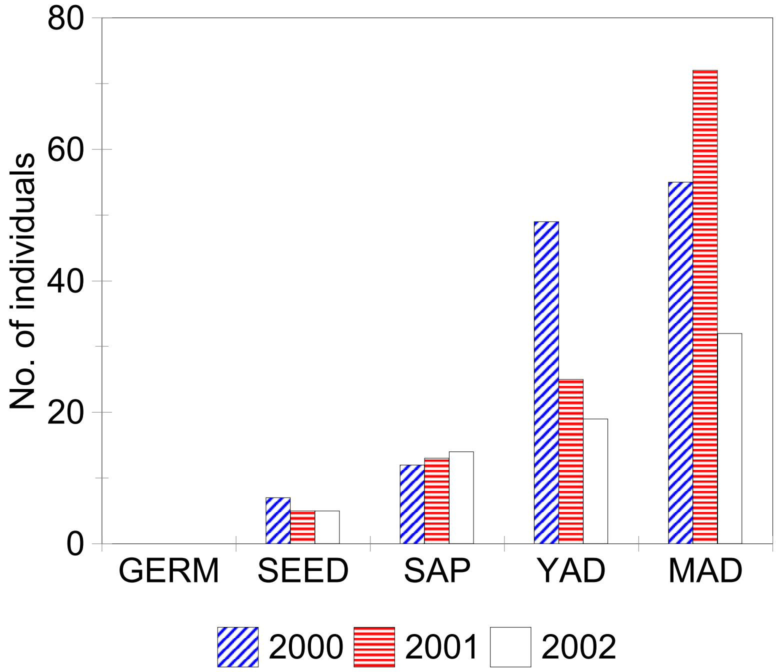

Figure 7.2 The number of *Breonadia salicina* individuals recorded in bedrock anastomosing channels in 2000, 2001, and 2002. GERM: germinants; SEED: seedlings; SAP: saplings; YAD: young adults; MAD: mature adults.

7.1.3 Use of the data for model refinement

Data collected from the three years of monitoring were intended for testing and refining the model. However, the magnitude and effect of the 2000 floods reduced the efficiency with which this was possible. The 2000 flood was categorized as a catastrophic flood in the *Breonadia* model. The TPC was thus predicted to be exceeded for four years, which was shown to be true for the three years in which monitoring was performed (Figure 7.1). However, this means that limited testing of the model was possible. The flood was fortuitous in that the effect of a catastrophic flood could be tested, but many other aspects of the model could not be tested within the duration of this project. It is essential that monitoring be continued to test the assumptions of the model, and to adjust it if necessary.

Table 7.1 Summary of *Breonadia* monitoring requirements (after MacKenzie *et al.*, 1999).

ESSENTIAL DATA				
Motivation	Data Type	What to Sample	When to Sample	Where to Sample
Audit TPC & Refine Model	Population density	Density of non germinant size classes	-Every 5 years -1st year after TPC excedence -5th year after no flow event or catastrophic flood -3rd year after large flood -2nd year after the last of 4 consecutive years of small floods	Rapid section of Pool-Rapid channel types
Test & Refine Model	Population density	Density of all size classes on actively, seasonally and ephemerally flooded substrate	Following a hydrological event until all events used in the model have been tested May/June	Rapid section of Pool-Rapid channel types
	Substrate Type	Proportion of each substrate type	As for Population density	As for population density
	Hydrology	Discharge ($m^3.s^{-1}$)	Daily	Closest gauging station to vegetation site
	Rainfall	Amount (mm)	Daily	Weather station <15 km from vegetation site
	Growth rates	Basal circumference of individuals of non germinant size classes X, Y, Z coordinates of individuals	Annually during low flow (May/ June)	Rapid section of Pool-Rapid channel types On all substrate types & inundation frequencies
USEFUL DATA				
Motivation	Data Type	What to Sample	When to Sample	Where to Sample
Refine Model	Survivorship	Mortality of marked individuals	No event followed by a hydrological event until all events have been monitored	Rapid section of Pool-Rapid channel types On all substrate types & inundation frequencies
	Fecundity	Number of germinants on each substrate type, number of adults in total sampling area	No Event & following a hydrological event until all events have been monitored	Rapid section of Pool-Rapid channel types
	Density Dependence	Nearest neighbor data on all substrate types & inundation frequencies	Once during a no flow period	Rapid section of Pool-Rapid channel types On all substrate types & inundation frequencies
	Herbivory	Survivorship in enclosed and non enclosed plots	Intermittently over a 10 year period	Rapid section of Pool- Rapid channel types

7.2 TERRESTRIALISATION MODEL

7.2.1 Monitoring plan for the Terrestrialisation Model

Within each site, counts of stage classes for each species are needed every three years, or after extreme hydrological events (catastrophic floods, large floods, and no-flow as defined in the model). Survival and density can be calculated from these data (Table 7.2). Individuals in each stage class must be marked, and these must be sampled every three years to calculate stage class longevity. Daily discharge and rainfall are needed, and data can be collected from the closest gauging and weather stations to the sites (Table 7.2), or can be generated by existing models such as ACRU (Schulze, 1995).

Hydrological states should be defined when monitoring is implemented, and must be redefined after every extreme flood (Table 5.1). The model defaults can be used, but it is more accurate to define the hydrological states for each site, rather than presuming that they are the same for different sites within a channel type. To define the states, the profile for the site is needed. From this, the stage of each hydrological state can be determined. A stage *versus* discharge curve is used to calculate discharge for each stage. This value is used in the model to define discharge for that hydrological state.

Table 7.2 Summary of Terrestrialisation monitoring requirements

Motivation	Data Type	What to Sample	When to Sample	Where to Sample
		Essential Data		
Audit TPC and refine model	Probability of occurrence	Counts of stage classes for each species	Every 3 years	Designated monitoring plots on features of different flow category
Refine parameter estimation	Survival	Calculate survival from above counts	Every 3 years and after hydrological events	As above
Refine parameter estimation	Size class longevity	Maximum longevity of all adult stage classes and saplings	Every 3 years	Sample marked individuals
Refine parameter estimation	Density	Calculate site density from above counts and convert to density for 5 X 5 m grids	Update every 3 years	
Model input	Hydrology	Discharge (m^3s^{-1})	Daily	Closest gauging station to site or ACRU (Schulze, 1995)
Model input	Rainfall	Total amount (mm)	Daily	Weather station closest to site or ACRU (Schulze, 1995)
Required to run the model for each site	Hydrological states	Define for each site	Once off and after major floods	At each site
Needed to define additional monitoring	Occurrence of hydrological events	Discharge (m^3s^{-1})	Annually	
		Useful Data		
Refine parameter estimation	Seed bank longevity	Germinability after seed collection	Annually	Experimental

Data that would be useful for refining seed bank longevities of species in the model are germinability over time. These data are labour intensive to collect however, and would be obtained by annual germination trials. At the start of the monitoring programme, at least 5000 seeds of each species would need to be collected from different trees, and stored. Each year, a certain proportion would be planted, and the proportion that germinates measured. From this, seed bank longevity can be estimated. One would expect the numbers that germinate to decrease with time as seeds lose germinability.

7.2.2 Location of the monitoring sites

Monitoring sites for the Terrestrialisation Model are located along the length of the Sabie River within the Kruger Park. Five sites were placed in braided channels, and four in mixed anastomosing channels, as these channel types were the most susceptible to terrestrialisation (Figures 4.3 and 4.4).

7.2.3 Ongoing Monitoring

One of the aims of the monitoring programme is to refine the Terrestrialisation Model within the SAM framework. An important aspect of SAM is that management is flexible, and can be adapted as necessary. Another aim of monitoring is to test the TPCs outside of the predictive framework. Ongoing monitoring will generate the data necessary to test TPCs under a variety of conditions, which will result in considerable improvement with regards setting TPCs and managing the ecosystem.

CHAPTER 8

TECHNOLOGY EXCHANGE AND ADOPTION

8.1 BACKGROUND

In the past the transfer of technology began with the premise or intuitive notion that the conduction of science led to the implementation of its products. Of course, this was a misconception and became known as “the strategy of hope”. This term described a *modus operandi* whereby scientists simply “hoped” that if they did good science, it would one day become useful to someone. The scientists themselves took no active steps to encourage or facilitate the transfer or adoption of their findings to relevant users. In fact, two misconceptions about the requirements of new technology are that 1) technological advances or discoveries usually are adopted eventually, and that 2) technological advances have intrinsic value (Steele, 1989 in Roux, 2001). The reality is that most technological developments fail to be adopted unless they offer substantial advantages, and even then their value is determined more by demand and not necessarily by characteristics of the product.

The historical setting at tertiary educational institutions in which scientific research developed, has been one where no or very little incentive was offered for directly engaging technology transfer, and so the strategy of hope became a common mindset among researchers. In addition, funding of scientific research was focussed on the acquisition of new knowledge and not the dissemination or impartation of this knowledge. Ecological research was no exception.

Now that funding agencies have shifted their foci, the transfer of technology has become an issue of importance. Researchers are faced with the difficult task of changing the strategy of hope syndrome, and engaging the process of transferring research products to users. But the onus for technology transfer surely is not, and cannot only fall to the researcher. For the process to be effective, technology transfer should equally be met by a mindset of technology adoption. This implies a co-ordinated effort from both researcher/developer and adopter/ implementer to catalyse the transferral and implementation of technology. Hence we have headed this chapter "Technology exchange and adoption" (TEA).

8.2 PRINCIPLES OF TEA

8.2.1 Joint Principles and User Buy-in

Conventionally, technology transfer comprised the development of research products (such as knowledge, data, rules, models, principles) that were largely developed in isolation of potential users of the products, and then marketed to encourage their acceptance and assimilation (Figure 8.1A). Two disadvantages are apparent with this system. First, the risk of failure of technology transfer is high. Second, the success of technology transfer is much more a function of marketing skills than of the properties of and needs for the product/s.

A more effective model of technology exchange and adoption is one where joint principles are established between developers and users at the initial/planning stage of technology development (Figure 8.1B). As technology development proceeds, these joint principles are reaffirmed and others may be developed. This process whereby interactions between developers and users are critical and necessary is likely to result in automatic buy-in of the new technology by end users. The potential also exists that by the end of development, the new technology would have become part of the user culture, thereby facilitating acceptance and assimilation with ease.

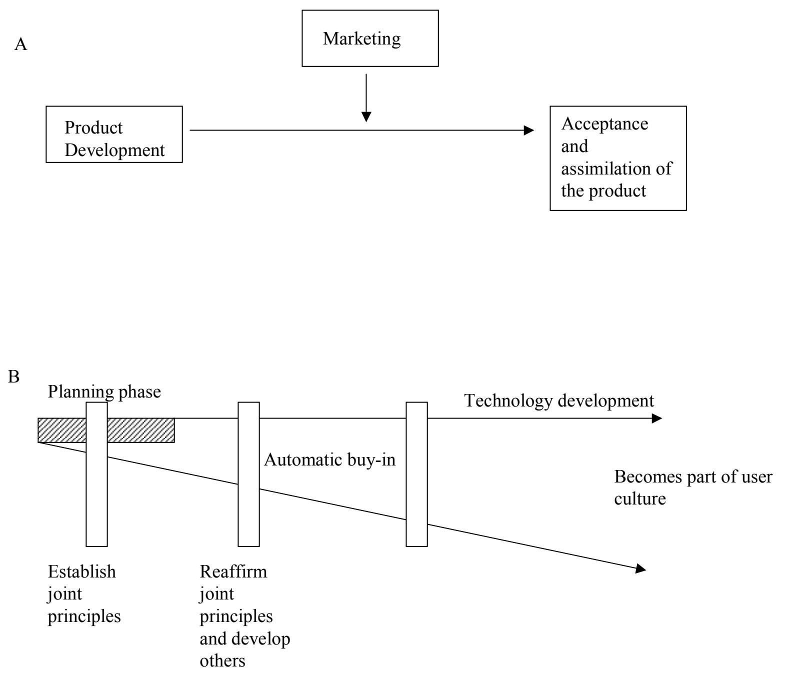

Figure 8.1 Conceptual models of traditional (A) and emerging (B) processes of technology exchange and adoption.

8.2.2 Demand Articulation

Demand articulation is the clear expression of what the users of technology need, with the express intention of guiding developers of technology to meet those needs. Demand articulation may range from a situation where potential users of technology explicitly outline their technological requirements, to a situation where developers of technology inform potential users of what their technological requirements are, and what possibilities exist to meet those. The latter situation is not as foolish as it sounds. The management of ecosystems is all too often impaired by a lack of even a basic understanding of how those systems function or respond to perturbations. Managers do not therefore have knowledge of what their needs are, and research is best employed to elucidate possibilities.

Demand articulation creates a context into which the products of technological advancement can slot. A good example of this is the Objectives Hierarchy that has been set by Kruger National Park and their associates. As its name implies, the objectives hierarchy begins with a broad vision-type statement, which is then decomposed into levels of increasingly detailed management objectives in a hierarchical fashion (Rogers and Bestbier, 1997). At the broadest scale, statements focus more on societal interest, but as statements become more detailed, more emphasis is placed on scientific rigour. The advantages of setting up an objectives hierarchy at the institutional level are numerous (see Rogers and Bestbier, 1997 for these), but we draw your attention to two.

The first advantage is connectivity. Because the hierarchy unfolds with increasing scientific and decreasing societal detail, science and public values are easily linked.

This means that scientific methods and products lower down in the hierarchy can easily be related to public values further up in the hierarchy. This not only gives purpose and direction to scientific efforts, but also justifies them in the public eye. This is important for TEA because violation or ignorance of societal values is sure to hinder the ultimate success of new technology.

Of course management also fits into the hierarchy. Statements of public interest are transformed into broad management objectives that are then decomposed into more specific management objectives. The more specific objectives become the more scientific they are. This important link between management and science is the 'make or break' of TEA. This is the second advantage we draw your attention to. The formalization of an objectives hierarchy creates a forum in which managers and researchers not only interact, but more importantly, articulate demands. Setting up the objectives hierarchy facilitates the establishment of joint principles between prospective developers and users of technological products, and sets the scene for user buy-in and assimilation to become more automatic.

8.2.3 Strategic Adaptive Management

Setting objectives, be they hierarchical or otherwise, is just one way of establishing joint principles, facilitating user buy-in and creating context for technological products. The subsequent arena in which TEA must play is also critical for its success. Bear in mind, both scientists and managers have been known to be wrong. A strategic approach that is also adaptive is therefore most likely to succeed in the exchange and adoption of technological products.

Strategic Adaptive Management (SAM) is recognised as an effective means of managing natural ecosystems (Rogers and Biggs, 1999), albeit with expected problems (Walters, 1997). SAM provides a framework that enhances the exchange and adoption of new technologies because 1) its strategic thrust calls for the setting of clear, achievable and operational management goals that create context for new product development and reception, and 2) its adaptive nature means that new products are less likely to become redundant as they are constantly and iteratively refined within the process of adaptation.

Once again, the KNP provides a good example of SAM facilitation of TEA (Figure 8.2). A Decision Support System (DSS) consists of research and a predictive and operational framework. First, agents of change and indicators of those agents are identified within the ecosystem of concern. Management objectives in the form of TPCs are then set using this information. Both modelling and monitoring are set in place to assess the achievement of management goals. This is strategic.

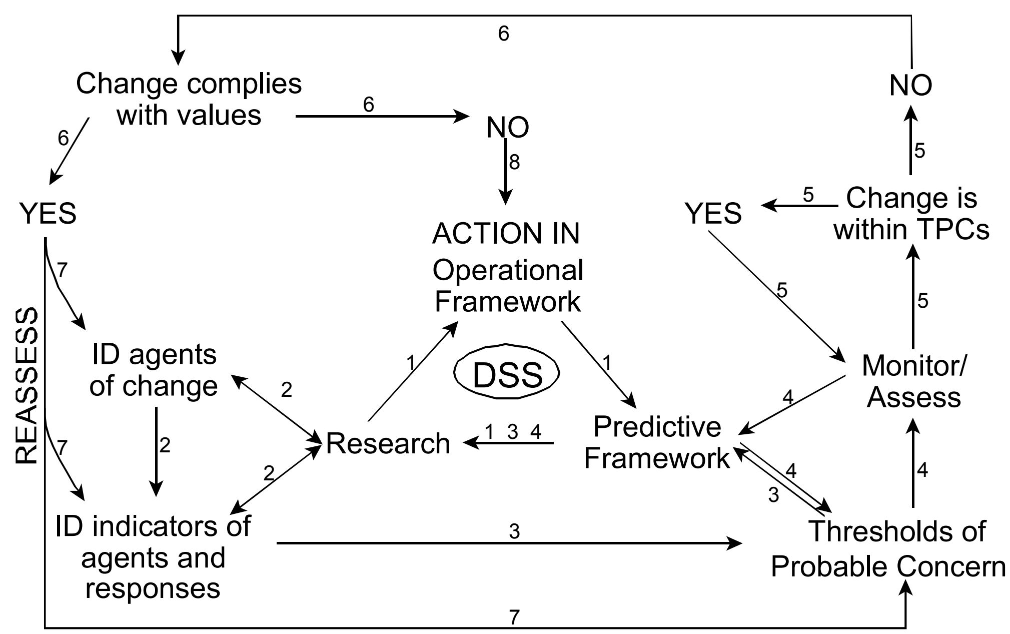

Figure 8.2. The iterative process of Strategic Adaptive Management used in the Kruger National Park (after Rogers and Biggs, 1999).

If TPCs are exceeded, they become subject to change, or the technologies used for their assessment may need refinement. This can occur via assessment in the predictive framework, which feeds back into research where tools and/or goals are scrutinized for improvement, or where changes in the ecosystem comply with exceedence of thresholds that are within broader values in the objectives hierarchy. This is adaptive. The SAM framework affords flexibility for the transfer, exchange and adoption processes, and encourages the evolution of technological products that will serve end users much longer and more efficiently.

8.2.4 Role Overlap and the Importance of People

The importance of interaction between developers and users of technology for effective exchange and adoption has already been alluded to, but cannot be overemphasised. Clearly, for TEA to be effective, teamwork is required.

It is usual for the people at any given organization or institute to relate to one another, or be arranged in the traditional hierarchical fashion (Figure 8.3A). In situations where TEA is envisioned, one would usually expect the interaction of at least two such organizations (Figure 8.3B). A case in point would be scientific services at KNP interacting with research groups such as CWE. The nature of the people within these organizations, as well as the nature of the interactions they cause, has direct influence on the success of TEA. Interactions could be a minimal client-service provider-type interaction (Figure 8.3B), or as in the case of KNP and research groups, interactions could be within the framework of SAM (Figure 8.3C). As already mentioned, there are advantages to employing a SAM framework, but if everyone in respective organizations were to 'just do their jobs', would TEA be successful?

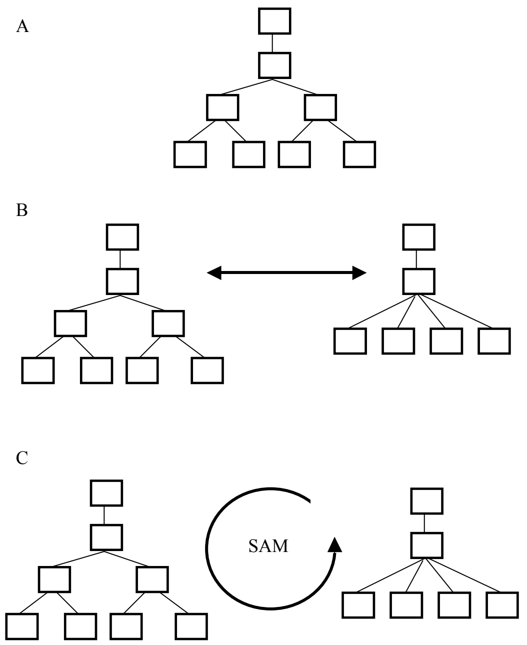

Figure 8.3. A schematic of the traditional arrangement of people at an organisation (A). Interactions between similarly arranged organisations can be minimal and simple (B) or more structured and complex such as within the framework of SAM (C).

We have already stated that both researchers and managers, in the traditional sense, have been stretched in their capabilities to facilitate and promote TEA, as they are required to consider the basic principles of one another's fields of discipline. It is our experience that this form of role overlap has been instrumental in the facilitation of TEA. But what really is role overlap and how much of it is needed for successful TEA?

Role overlap can be defined in many ways. We outline two facets of role overlap and suggest that these are crucial to effective TEA. Agreeably, for the conservation or sustainability of natural ecosystems, decision making, knowledge management and operations (consisting of research, monitoring and management) are required. These roles are schematically represented as points in a triangle, with respective arms of the triangle representing conduction or completion of the role (Figure 8.4A). Admittedly, each of these roles can function in isolation, but TEA is then unlikely to be unsuccessful.

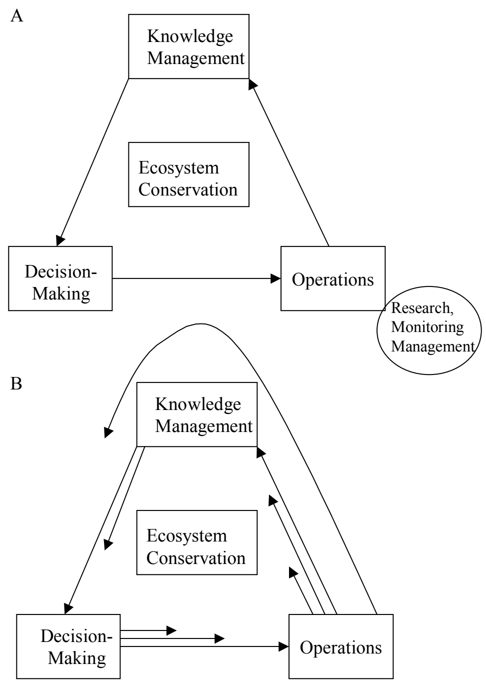

Figure 8.4. Schematic of the roles necessary for ecosystem conservation operating in isolation (A) and with interaction and role overlap (B).

In a usual ecosystem conservation setting, teams of people will conduct each of these roles. In outlining Figure 8.4A, it was assumed that each role was conducted sufficiently effectively by each team. The overall capability to perform each role, however, will be limited by capacity. People with restricted capacity will not generally engage in role overlap (represented by the short arrows of the triangle in Figure 8.4B). Some people are sufficiently capable (complete arrows in the triangle), but also do not engage in role overlap, while few people take an active interest in other roles and engage them to some degree (arrows that round points of the triangle). These, for example, are managers or researchers that also engage knowledge management and/or decision-making.

Another form of role overlap that we suggest is beneficial to effective TEA is experience of, or background to other roles or disciplines. TEA is less likely to succeed when interacting teams have no experience or background of one another's roles. This is schematically represented by two hierarchical organizations conducting different roles, for example research and management, with no role overlap along a theoretical-practical gradient, which in this case is a traditional measure of the differences between these roles (Figure 8.5A).

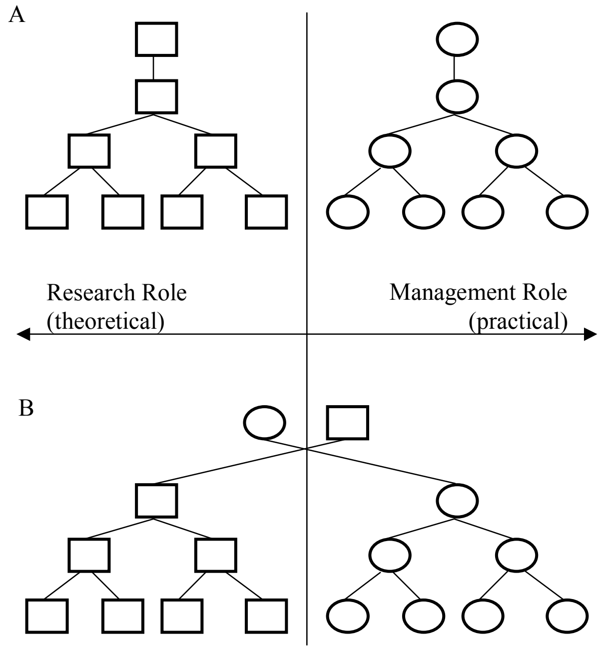

Figure 8.5 Schematic of hierarchical organisations with different roles where there is no role overlap (A), and where role overlap exists (B).

A more effective way to encourage TEA would be a situation where one or more of the team members representing each role were to, at the very least, express an active interest in other roles, but preferably, to have had experience in performing other roles (Figure 8.5B). Managers who, for example, have come from a scientific background, or who have scientists in their team, would fit this description.

8.3 TEA WITHIN THE KRUGER NATIONAL PARK

We learnt a great deal about technology exchange and adoption through our experience with transferring the results of the project to researchers and managers in the Kruger National Park. Some of our experiences are discussed below.

8.3.1 Existing factors which assisted TEA

- An objectives hierarchy was already in place when the project started. Demand articulation was thus a simple and automatic process.
- Some of the KNP researchers were already involved in committees that decided on research projects, and some were already involved in river management. Needs were thus realistically filtered by KNP.
- River issues were taken seriously, and river management was seen as a high priority.
- Outside stakeholders, especially scientists, were actively involved. This improved credibility and buy-in, and increased the chances of success.

8.3.2 Existing factors which hindered TEA

- Conventional management cadres were not involved in the beginning. Their involvement only started later, and increased slowly and with difficulty. Even the KNP researchers who were already involved in committees (Section 8.3.1) initially struggled to take responsibility and kept looking to either (a) DWAF for command-and-control solutions and/or (b) to the KNPRRP to assist them. This "weaning" process was traumatic and needed repeated "stand-ins" by the KNPRRP, and special TEA type sessions. The difficulties were partly due to the fact that the driving factors were outside KNP, and so KNP researchers had none of the normal confidence they had developed on internal matters. However, the growth and spread of this responsibility ultimately became very successful, with multiple "river champions" emerging. In addition, outside partners are regularly employed to assist and lend support.

- Although a retrenchment process shifted the "river post" back to research (after a long battle to get it into management) supervisors responded by shifting most of the responsibilities with the person. Thus, despite the threat that this change posed to the process, no difficulties were experienced. This highlights the understanding and commitment that exists at various levels.
- Staff turnover led to some problems. One example is that a new employee was given responsibilities without sufficient knowledge, which hindered the process to some extent. Although levels of turnover within KNP are generally low, this issue should be considered.
- Several staff members who were not conversant with modelling found this emphasis intimidating and confusing. However, the problem was overcome with time, and by building the realization that one does not have to be a modeller to work constructively with modellers, and to use their products.

8.3.3 Individual Responses

Individual responses within the research and management communities in KNP varied. There was a continuum from "passive resistance mode" to "enhancement mode".

Passive resistance mode

An attitude is projected by certain KNP staff that outside researchers doing research within KNP are a nuisance. However, they are tolerated because their research may be of use to management, but they are given no encouragement or support. Their results are only used if managers are convinced of their value, and are told exactly how to apply them. This attitude is not conducive to successful TEA.

Enhancement Mode

There is an attitude that outside researchers are working with KNP staff to mutual benefit. The researchers and managers understand that the results are needed, and provide whatever support is necessary. Problems are addressed by both the KNP staff and the outsiders, so that acceptable solutions are found. KNP staff are involved throughout the project, and implementation is thus relatively problem free.

Although these two extremes of the continuum may seem a bit caricatured (passive resistance) or idealistic (enhancement), they certainly exist sufficiently to be useful as descriptors. A challenge is that if one of the partners is reneging, providing too little support, or simply not caring, the enhancement mode will eventually break down. One partner cannot make up for continual low levels of performance in the other partner. Shifting the attitude from passive resistance to enhancement is an important action, which is associated with success. However, if passive resistance continues to exist (or starts to develop) some serious questions should be asked. The relationship may be at the point of breaking down, or partners may be losing faith in the particular research process. These issues must be addressed as soon as they become apparent.

Members of KNP staff have identified a major deficiency in their own processing of results, in that a formal knowledge harvest for their own purpose is seldom carried out. This needs to be done by a KNP scientist with the necessary background, and then be extended formally and effectively to managers. This will receive far more attention in future.

8.3.4 Role Overlap

- KNP was fortunate in always having a formally constituted joint research-management forum with some power.
- On this forum there were always a few individuals with key role overlap. For example, at the present time the Manager of Scientific Services has much practical credence, as well as a thorough understanding of SAM and the science-management links. Conversely, many senior managers show detailed understanding of research, as well as being successful managers. Most senior managers and rangers are understanding towards researchers, even if they have no personal scientific experience. Unfortunately, a minority can become hostile at times.
- Within any organization there are certain key personality types, which play a critical role in management. These include individuals who act as "visionaries", "integrators", and "loyal heretics" (Gunderson *et al.*, 1995a). These individuals encourage interactions within and between organizations, and encourage change when it appears necessary. Gunderson *et al.* (1995b) list six types of individuals who exert substantial influence by performing distinct roles within and outside an institution. All six types of individuals exist within the KNP, and each performs an important role. However, even

without the presence of key individuals, TEA can be successful if the recommendations given in Section 8.4 are followed.

8.4 LESSONS AND RECOMMENDATIONS

In the following section, we outline lessons that we have learnt with respect to TEA, during the course of developing, exchanging, and adopting both the *Breonadia* and Terrestrialisation Models and their associated TPCs, as well as recommendations for more effective TEA:

1. For potential users of new technologies to be aware of, and approve the development of new technological products, is not necessarily enough to ensure effective TEA.
2. Users and developers of new technologies should be prepared, and expect to define joint principles at both the planning and development phases.
3. Problem and/or goal definition should precede technological advancement, and should not be divorced from institutional/organizational structure, function and peculiarities.
4. Technological products should be the result of team effort. This means that prospective users should not only be aware of planning and progress (attending steering committee meetings for example), but should be incorporated in the actual development at relevant levels.
5. Technological products should be developed with flexibility to change or be refined with use, and should embrace the framework of SAM.

6. Prospective users of new technologies should prepare themselves (at least at the personal scale, but preferably at the corporate scale) to be strategic and adaptive in their roles.
7. Utilization of and interaction with key personalities should be pursued when engaging TEA.
8. Prospective users of new technologies should make an effort to promote buy-in and use. This is a recognised recommendation as outlined by the following quote from minutes of a workshop held on July 18, 2001 to discuss the research and technology transfer process:

   "3.1.2 **Dr Mitchell** suggested that the users should act as a third signatory to the contract to ensure that technology transfer would happen. **Dr Biggs** went further to say that they should not only sign it, but the level of handover responsibility should be specified (e.g., for a modelling based project would it constitute a report, scenarios, an installed modelling system, or a running software product with training given). **Dr Mkhize** noted that these agreements would have to be tailor-made for each project and could not be a standard/form document."
9. Some members of each team should, at least in principle, be prepared to engage role overlap.
10. Corporate structures that promote SAM frameworks should be encouraged, and developers and users alike should prepare themselves to embrace these structures.
11. Multilevel interactions between organizations are likely to result in more effective TEA than single level interactions (Figure 8.6). A technological product (P) that is developed by one organization and adopted by another is

less likely to succeed if only the developer and user interact (Figure 8.6A). Multilevel interaction is required, not only within organizations, but between them (Figure 8.6B), and these interactions should centre around the technology being developed and adopted as well as the supportive environment in which TEA will take place.

8.5 PROTOCOL

In attempting to set up a protocol to guide and promote TEA, we have focussed on thrusts and attitudes that are likely to facilitate effective TEA. These thrusts and attitudes are properties of the people that engage TEA and will be dependent on the environment in which they occur.

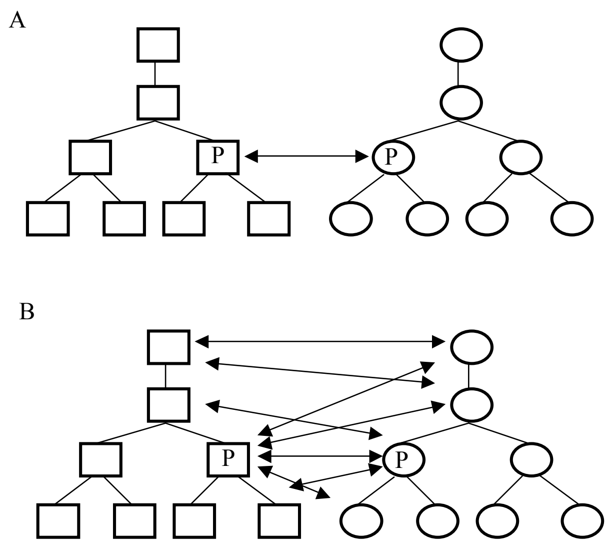

Figure 8.6. Schematic illustrating single-(A) and multi-level (B) interactions between organisations engaged in TEA for a specific product (P).

We have defined three environments (Figure 8.7). The internal environments of 1) developers, 2) adopters, and 3) a multi-level interactive environment in which TEA takes place. The following thrusts and attitudes should characterise the Internal Developer Environment,

1. Development should begin with problem articulation
2. Development should be objective driven
3. Developers should produce high quality, relevant products that are designed to be flexible and refined
4. Scientific rigour should be pursued

whereas the Internal Adopter Environment should be characterised by the following thrusts and attitudes:

1. Adopters should engage demand articulation.
2. Adopters should actively participate in the development of new technologies.
3. Adopters should cultivate an attitude of buy-in within themselves and their organization.

Multi-level interactions between developer and adopter organizations create the environment in which TEA takes place. These interactions should be characterised by thrusts and attitudes that:

1. Define joint principles at both planning and development phases
2. Embrace frameworks that facilitate TEA, such as SAM
3. Encourage SAM frameworks
4. Engage role overlap
5. Pursue networking between people and organizations where multi-level interactions are frequent and engage feedback mechanisms

6. Recognise and utilise key personalities.

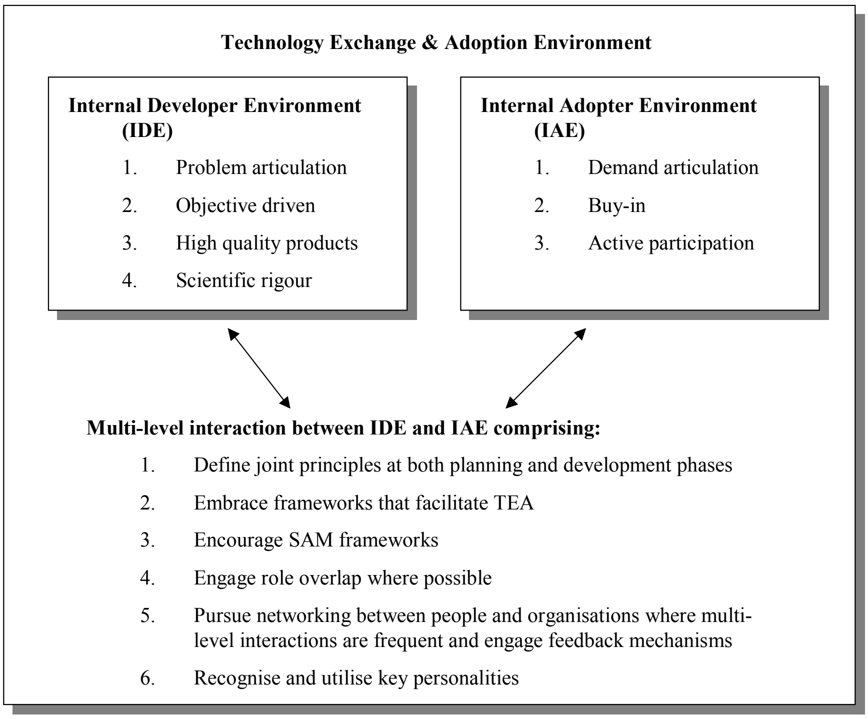

Figure 8.7 Protocol for Technology Exchange and Adoption.

CHAPTER 9

CONCLUSION

The Sabie River is threatened by changes in land use, which are occurring upstream of the Kruger Park. One of the effects of catchment development is an increase in terrestrial species encroaching into the riparian zone, causing reduced heterogeneity and diversity of riparian species. However, this phenomenon has not been researched in detail, especially along South African rivers. Our study therefore focused specifically on the encroachment of terrestrial individuals into the riparian zone.

9.1 TERRESTRIALISATION

Terrestrial species occurring in the savanna may also occur within the riparian zone, but decrease in abundance with reduced distance from the active channel. We define the process of terrestrialisation as a progressive increase in the abundance of terrestrial individuals relative to the abundance of riparian individuals within the riparian zone. We hypothesize that the processes or agents of change underlying an increase in terrestrial species in the riparian zone are a reduction in flooding frequency for a given stage, reduced water availability from the water table, and increased sediment accumulation on bars.

We found that ephemerally flooded geomorphic features were much more susceptible to terrestrialisation than were actively or seasonally flooded features. The number of terrestrial individuals increased along a gradient of decreasing flooding frequency, which suggests that frequent flooding limits terrestrialisation.

Braided and mixed anastomosing channels were most susceptible to terrestrialization, and bedrock anastomosing channels least susceptible. The process of terrestrialization was found to be limited by the presence of bedrock, and facilitated by the presence of sediment. The same observation was made at the geomorphic unit scale, where the macro-channel bank was the most susceptible geomorphic feature in terms of terrestrialistation. All features associated with sediment had greater numbers of terrestrial individuals than did features associated with bedrock.

Managers within the KNP use thresholds of probable concern (TPCs) to alert them to unacceptable change occurring in ecosystems. We suggest separate TPCs for the three categories of flow, and set a T:R ratio of 6 as the TPC on ephemerally flooded features, 1 on seasonally flooded features, and 0.2 on actively flooded features. However, these TPCs are a first estimate, and must be refined or changed if the monitoring programme shows this to be necessary.

9.2 NATURAL RESOURCE MANAGEMENT

Management of the KNP is based on strategic adaptive management (SAM), of which research is an important component. A decision support system (DSS) provides a technological interface between management and research. KNP managers have described the desired state of the rivers, and use operational goals to ensure that this state is achieved. Monitoring is a critical aspect of management, as it allows goals to be audited to ensure that ecosystem change is towards the desired state.

An essential component of management is a predictive modelling framework that enables prediction of the consequences of management actions. It is within this framework that predictive tools such as rule based models are utilized.

9.3 PREDICTIVE MODELS

We developed two rule-based models (the *Breonadia* and the Terrestrialisation Models) that can be used in predictive management. The *Breonadia* Model has value as a management tool because it:

- Predicts the population response of *Breonadia salicina* to rainfall, hydrology and geomorphology.
- Audits the TPC for the loss of bedrock influence, of which *B. salicina* is an indicator.
- Provides decision makers with a formal protocol for using TPC audits in decision making.

- Can be used to generate and evaluate scenarios of the consequences of change in catchment characteristics and processes.
- Enables users to easily interpret results by presenting input and rule summaries with outputs.
- Can easily incorporate monitored data to improve parameter estimates.
- Utilizes a user-friendly interface and graphical presentation of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.
- Together with the Help manual, can be downloaded from the Internet.

The Terrestrialisation Model has value as a management tool because it:

- Predicts encroachment into the riparian zone by terrestrial individuals.
- Audits the Terrestrialisation TPC.
- Can be used to generate and evaluate scenarios of the consequences of change in catchment characteristics and processes.
- Enables users to easily interpret results by presenting input and rule summaries with outputs.
- Can easily incorporate monitored data to improve parameter estimates.
- Utilizes a user-friendly interface and graphical presentation of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.
- Together with Help facilities, can be downloaded from the Internet.

All models are based on certain assumptions. Those of the *Breonadia* Model include:

1. High flows (20-120 m^3s^{-1}) and very small floods (120-300 m^3s^{-1}) have no

influence in the model, while extreme low flows (0-1 m^3s^{-1}) to intermediate flows (5-20 m^3s^{-1}) are only used to determine the occurrence of a drought event.

2. Growth rates are independent of substrate type and inundation frequency.
3. Drought and rainfall do not influence growth rate.
4. Damage caused by flooding reduces growth rate of an individual.
5. Size classes cannot skip a size class (e.g. germinants to saplings).
6. Density dependence is independent of substrate type and inundation frequency.
7. All adult size classes have the same density dependence affecting their survival.
8. Fecundity is independent of substrate type.
9. All adult size classes have the same density dependence affecting their fecundity.
10. The influence of a hydrological event overrides the influence of all other hydrological events (i.e., there are no combined influences of hydrological events).
11. Herbivory does not influence the *B. salicina* population.
12. Equal densities of the *B. salicina* population on different substrate types are assumed in the calculation of the vector matrix.

Assumptions of the Terrestrialisation Model include:

1. Only 1 species can occupy any 5x5m grid cell in the initial vegetation stage.
2. Regeneration is not seed limited.
3. Only mature adults disperse significantly.

4. Dispersal occurs at the end of the growing season.
5. Seeds dispersed into the water die or pass through the modelled site.
6. Fire, herbivory and animal dispersal do not contribute significantly to vegetation processes within the riparian zone.
7. None of the key species occurs on exposed bedrock.
8. Geomorphological change is less important for terrestrialisation than flow regimes. (Our data support this assumption. Refer to Chapter 4.)

As models always need some refinement, a monitoring programme is essential to provide data to improve the predictive capability of the model.

9.4 MONITORING PROGRAMME

Monitoring is needed to test the hypotheses on which adaptive management is based, and can be used to audit the goals or TPCs. A critical role of monitoring is the collection of data for model refinement and improvement of its predictive capability.

In order to refine the *Breondadia* Model we collected data annually from 2000 to 2002. Within sites in bedrock anastomosing and pool-rapid channels every individual was recorded, and its stage class was noted. From this, the state of the population was investigated, and the model was updated. We found that populations in pool-rapid channels were more severely damaged by the flood of February 2000, than were populations in bedrock anastomosing channels. The catastrophic flood which the Sabie River experienced during the study proved useful in model refinement. It is essential, however, that monitoring be continued to further refine the model.

We also described a monitoring programme to allow refinement of the Terrestrialisation Model. Sites were selected in braided and mixed anastomosing channels, as these channel types are most susceptible to terrestrialisation. Within each site, counts of stage classes for each species are needed every three years, or after extreme hydrological events. From these, survival and density can be calculated. Individuals in each stage class must be marked, and these must be sampled every three years to calculate stage class longevity. Daily discharge and rainfall are needed, and data can be collected from the closest gauging and weather stations to the sites, or can be generated by existing models.

From the monitoring programmes, both models can be refined. In addition, the SAM framework ensures that management is flexible, and can be adapted as necessary. Monitoring will highlight necessary change. Another aim of monitoring is to test TPCs to ensure that none is being violated. Ongoing monitoring also allows managers to ensure that change is in the direction of the desired state. Monitoring programmes thus enable more successful management of the ecosystem.

9.5 TECHNOLOGY EXCHANGE AND ADOPTION

During the study we developed new technology. This technology has been exchanged with end users, who have adopted it. We also developed a protocol for technology transfer, which will be useful to other researchers involved in developing, exchanging, or adopting technology. The direct involvement of the end-users at every stage of the project has been shown to lead to greater success than the "strategy of hope" policy, in which the developers presumed that the users would find their products useful, and would automatically adopt them. An important component of technology exchange and adoption (TEA) is demand articulation, which is the clear expression of what the users of technology need so that developers of technology are guided by a definite need, rather than a vague idea of what the users require.

Recommendations for successful TEA include:

- Joint principles between developers and users should be defined at both the planning and development phases.
- Problem and goal definition should precede technological advancement.
- Technological products should be the result of team effort. Users should thus take an active role in all stages of development.
- Technological products should be developed with flexibility to change or be refined with use, and should embrace the framework of SAM.
- Users of new technologies should be strategic and adaptive in their roles.
- There should be role overlap between developers and users.
- There should be multilevel interactions between organizations involved in product development and those who will use the product.

We found that the most important principles underlying technology transfer and adoption are an attitude of flexibility, interaction, and involvement of both developers and users. Interaction between developers and users, and a clear idea of users' needs are critical at all stages of product development to reduce the complexity of technology transfer. Adoption is then likely to be an automatic process.

9.6 RECOMMENDATIONS FOR FUTURE RESEARCH

It is extremely important that both the *Breonadia* and the Terrestrialisation monitoring programmes described above are continued, in order to refine the models and the TPCs.

A rule based model to manage alien vegetation invasions is urgently needed. The Terrestrialisation Model could be adapted to meet this need, and a monitoring programme implemented.

An understanding of the expansion and contraction of reed populations is needed, as reeds act as engineers, affecting river structure and function. A rule based model which allows managers to predict changes in reed population size will greatly assist management.

APPENDIX

CAPACITY BUILDING

It is the policy of the WRC that research projects engage capacity building in its broadest context, but especially amongst previously disadvantaged communities, institutes and individuals. The present project has embraced capacity building in the following ways:

- The project's research complement addresses gender imbalances in that it includes one male and one female.
- Two individuals received practical training in the use of the programming language Visual Basic for coding of rule-based models (Lesego Khomo and Robbie Kröger), and they participated in writing sections of the code. The building of models is not taught in undergraduate or postgraduate biological curricula, and the training was therefore highly beneficial to these individuals, who are MSc students.
- Postgraduate students within CWE were invited to participate in field trips to learn and experience methods of data collection used in vegetation science.
- The modelling capacity of individuals (those mentioned above and KNP staff) and institutes (CWE and KNP) has been improved. The *Breonadia* Model has been transferred to senior scientists and managers at KNP, and various meetings/workshops have been held to discuss and demonstrate model use as an assistant to decision making.

- Meetings/workshops have also been held with staff from Scientific Services (KNP) to discuss and guide the conceptualization and development of the "Terrestrialisation" Model. This model, like the *Breonadia* Model, will improve the capacity of managers in the decision making and strategic adaptive management processes.
- Eddie Mabena, a Black second year student, was employed to convert the *Breonadia* User manual into html text. This required him to receive training in Web design, and he thus gained valuable computer skills which will assist him in the future.

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