RULE BASED MODELLING FOR MANAGEMENT OF RIPARIAN SYSTEMS

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Water Research Commission

RULE BASED MODELLING FOR MANAGEMENT OF RIPARIAN SYSTEMS

by

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"Rule Based Modelling for Management of Riparian Systems"

Project Leader: **Professor K.H. Rogers**

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EXECUTIVE SUMMARY

MOTIVATION AND RATIONALE

Legally, only one right to water is specified in the National Water Act; that of the Reserve (White Paper, 1997; National Water Act News, 1999). The Reserve consists of two parts:

- **The basic human needs Reserve**, which includes water for drinking, food preparation and personal hygiene.
- **The ecological Reserve**, which must be determined for all or part of any significant water resource such as rivers, streams, wetlands, lakes, estuaries and groundwater.

The Reserve must specify the quantity and quality of the water which will maintain the resource in an ecologically healthy condition and provide the basic human needs for water. All water uses under the National Water Act are subject to the requirements of the Reserve. Thus, licences for different types of water use cannot be issued without the Reserve having been determined.

Managers of a water resource are therefore faced with the task of determining the ecological Reserve in their area. All other uses of the water resource are then authorised according to the criteria of equitable allocations, beneficial use in the public interest, and promoting environmental values. These allocations are the responsibility of Catchment Management Agencies, in which conservation managers are usually involved. The difficulty of quantitatively justifying water demands for environmental use has weakened the bargaining power of conservation. Biologists and conservationists quantify water demands (justifiably so), with difficulty due to the complex nature of the systems they represent and manage and are therefore in need of tools such as the *Breonadia* model, that serve to quantitatively address the desired state (Rogers and Bestbier, 1997) of rivers in the catchment by being able to determine and justify the ecological Reserve.

In the Kruger National Park Rivers Research Programme (KNPRRP) context, and specifically in the Sabie River catchment, we have developed a model that, though specialized in its application, empowers the bargaining power of conservation managers around the table of catchment role players. The model is essentially a river-section-scale tool (quantitative solicitation of a causal chain of our assumptions) that can be applied to catchment-scale decisions or actions.

Riparian vegetation plays a direct, key role in the functioning of river systems through its effects on water quality, hydrology (transpiration), hydrualics (flow resistance), sediment stabilisation and trophic processes (Rogers & van der Zel, 1989). Riparian systems are also major contributors to regional and global biodiversity (Naiman *et al.*, 1993).

Studies on South African rivers are few (Rogers, 1995) and our ability to manage them according to their flow requirements is limited. In particular we lack the ability to predict a response of riparian vegetation to changes in flow and geomorphology, the two primary determinants of riparian vegetation structure and composition.

Studies on the Sabie River (van Coller, 1993; van Niekerk & Heritage, 1993; Chesire, 1994; Carter & Rogers, 1995; de Fontaine & Rogers, 1995; Heritage *et al.*, 1997; van Coller & Rogers, 1995, 1996; Birkhead *et al.*, 1997; Mackenzie & Rogers, 1998) provide the current understanding with the potential to develop management and predictive capabilities. A prototype predictive model of the response of riparian vegetation to flow and geomorphological change in the Sabie River was developed (the BLINKS riparian vegetation model) by the Centre for Water in the Environment (CWE) in conjunction with the Civil Engineering Department of Stellenbosch (Jewitt *et al.*, 1998) under the auspices of the Kruger National Park Rivers Research Programme (KNPRRP) (Breen *et al.*, 1994). Time constraints did not allow for adequate model development and there was therefore the need and opportunity to further develop and improve the BLINKS riparian vegetation model.

It is imperative that the expertise developed on the Sabie River be extended beyond the KNPRRP as the second objective of that programme requires (Breen *et al.*, 1994) .

One means of ensuring better transfer of predictive capability and modelling expertise to the broader research community is to develop a set of guidelines which explain the steps to be taken in developing, testing and using such models. There was therefore a need to formalise an approach to studies aimed at developing and using predictive rule based models, especially as management tools. Experience gained from this project was therefore used to develop a generic protocol that will assist and guide researchers and managers in the future.

RESEARCH AIMS AND OBJECTIVES

The overall aim of this project was to improve the national potential to manage the response of riparian systems to changes in flow regime and geomorphology. In order to achieve this aim the following specific objectives were pursued:

- Evaluate the riparian vegetation abiotic/biotic links model of the Sabie River that was developed by the KNPRRP to ascertain additional knowledge and data needs for improved decision support.
- In the light of this evaluation, improve the knowledge base by assessing the response of vegetation and geomorphology of the Sabie River to the recent severe droughts (1992 & 1995) and floods (1996).
- Refine or if necessary redesign the 1996 prototype riparian abiotic/biotic links model in order to address specific management goals.
- Develop a monitoring programme for evaluation of achievement of riparian management goals for the Sabie River.
- Produce a protocol for the development, testing and use of rule based models as decision support tools for river management.

These objectives are not in any order of priority, but are in a sequence which allowed an incremental and iterative approach to their achievement.

ACHIEVEMENT OF STATED OBJECTIVES

Evaluation of the BLINKS riparian vegetation model

The BLINKS riparian vegetation model was iteratively evaluated in terms of:

- Scrutiny of model constraints and assumptions
- Parsimony of the model structure and its use
- Potential to provide decision support for management and to define research to improve decision support
- Extent of knowledge base use and potential to incorporate additional data
- Ability to generate auditable output

The conclusion was that decision support was limited because the model output did not serve particular decision making needs, there were too many critical assumptions in the model, the output was too coarse and the temporal framework was inadequate. The model could also not be used to adequately define research needs to improve decision support because it lacked critical ecological complexity. The potential existed to markedly improve the model mechanism, data base and usefulness with a pragmatic rule based approach.

Improvement of the knowledge base

This exercise was aimed primarily at capturing the response of riparian vegetation to events such as droughts and floods, which the BLINKS riparian vegetation model could not incorporate. An extreme drought which occurred during the wet season of 1992/1993 resulted in the death of numerous riparian trees (van Coller & Rogers, 1996), and a flood event with an estimated one in fifty year return period occurred in February 1996. This provided the opportunity to collect information on the response of riparian vegetation to both kinds of events.

Vegetation response to the flood was measured at the species and within river landscape type (rock, sand, reeds and shrubs, shrubs, and trees) levels. Existing surveyed transects (sampled in 1990) were re-sampled at the end of 1996 to determine the extent of loss, death and damage of individuals. Vegetation response to the drought was recorded from an aerial census to determine the overall extent of mortality and a ground census where mortality and degree of stress were recorded on existing survey transects. Relationships between mortality / stress, elevation above, and horizontal distance away from the channel, discharge, and morphological units were established.

This improved knowledge base provided vital information and data for the refinement of the BLINKS riparian vegetation model.

Refinement of the BLINKS riparian vegetation model

Seven steps were iterated to refine and develop the BLINKS riparian vegetation model:

1. Redesigning the conceptual models to define management problems and model objectives

2. Converting the knowledge base into rules
3. Designing the inference engine of the model
4. Converting the model into auditable output
5. Validating the model and evaluating the TPC
6. Testing the model
7. Conducting sensitivity analyses

Redesigning conceptual models to define problems and objectives

A pragmatic approach to modelling was adopted (Starfield, 1997) whereby small objective driven models were developed, each a single purpose management tool. The major management problems along KNP rivers are loss of bedrock influence in the macro-channel, terrestrialization of the riparian zone, invasion of the riparian zone by alien vegetation and encroachment by reeds (Fig. i). Management goals, or Thresholds of Probable Concern (TPCs) (Rogers & Bestbier,

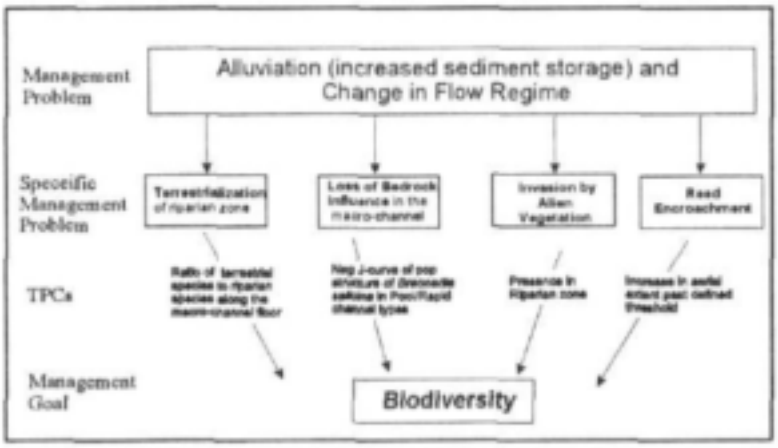

Figure i. Major management problems and their associated TPCs.

1997) , were defined for each problem, and used to guide conceptual model development for each problem by using assumptions to mask complexity (Fig. ii).

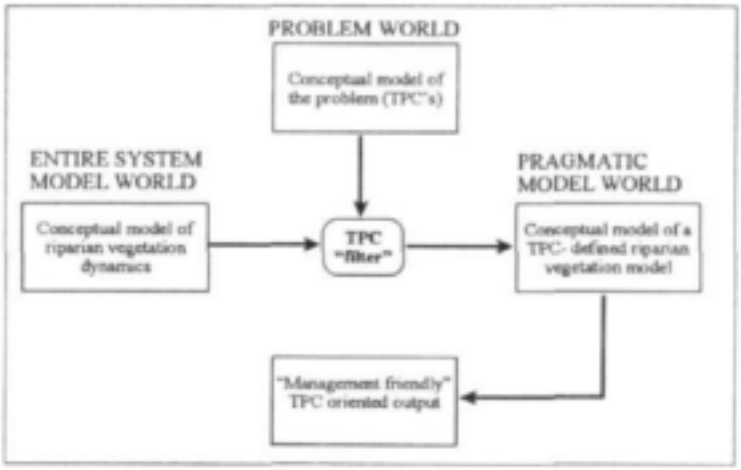

Figure ii The use of TPCs in guiding pragmatic model world development.

The TPC for the terrestrialization of the riparian zone was defined as 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 (Fig. iii). The resultant pragmatic model world for the terrestrialization TPC consists of interactions between terrestrial and riparian species life history strategies and with environmental factors (Fig. iv).

The TPC for the loss of bedrock influence in the macro channel focused on the riparian tree species, *Breonadia salicina* as an indicator of exposed bedrock presence. The TPC was defined as the persistence of a negative J-shaped population structure for all non-germinant individuals of *B. salicina*. The resultant pragmatic model world for the loss of bedrock influence is a standard size class population matrix model (Fig. v), that is rule based and deterministic. Inputs include rainfall (in the form of daily values and states), hydrology (in the form of hydrological states; Table i), geomorphology (in the form of substrate types), and growth rates (in the form of size class longevity). Inputs and feedbacks determine the following matrix values: fecundity, survival, and the probability of staying in a size class or going to the next size class. Feedback mechanisms include adult abundance effects on fecundity, density dependence effects on survival and fecundity for each size class, and population structure at the next time interval.

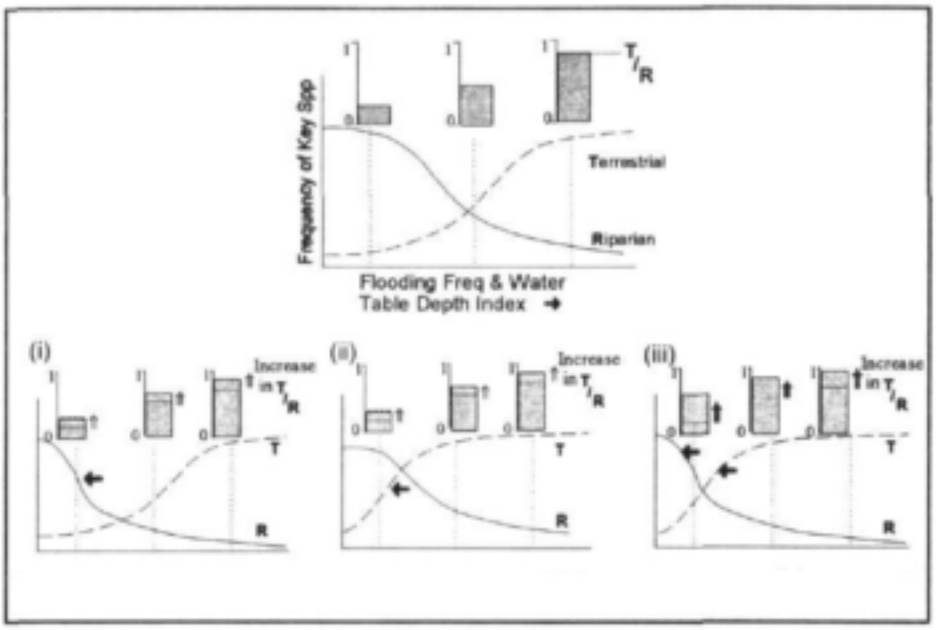

Figure iii. TPC for terrestrialization of the riparian zone. The TPC is the ratio of terrestrial (T) to riparian (R) species along a flow frequency / water table depth gradient.

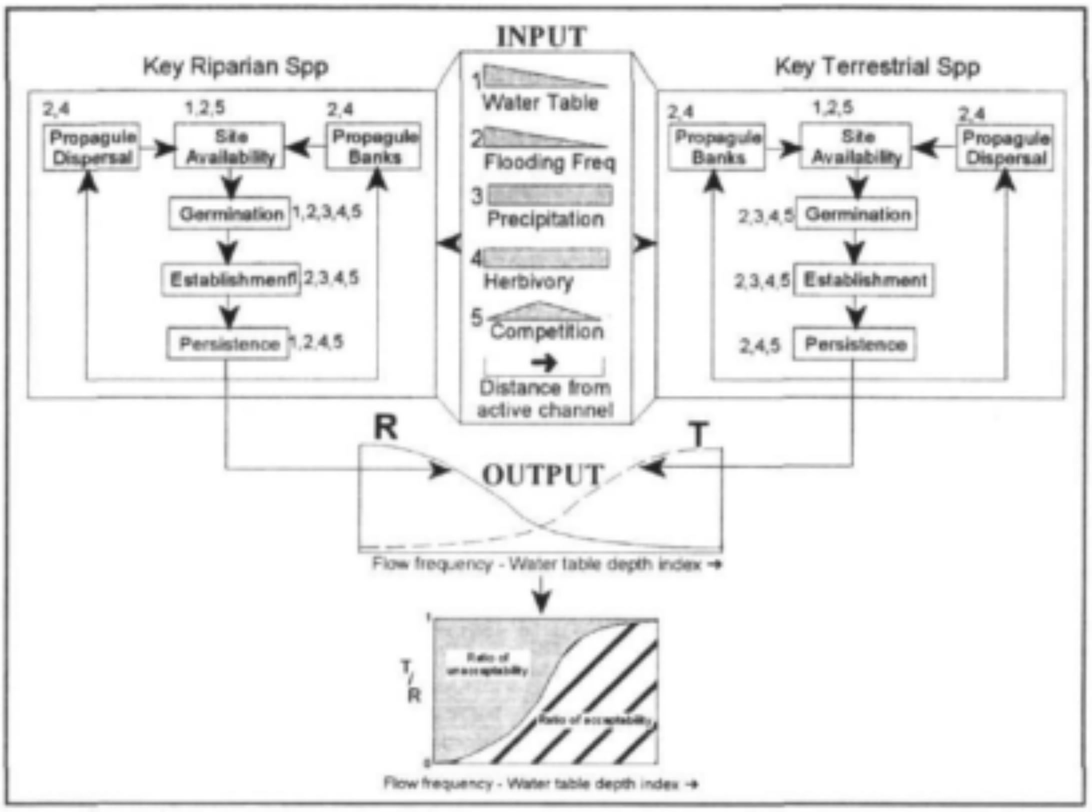

Figure iv Conceptualisation of the pragmatic model world for the terrestrialisation TPC, showing inputs and outputs of the model. The numbers in the key riparian and terrestrial species boxes correspond to the numbers in the input box. T and R are terrestrial and riparian species respectively.

The presence of alien vegetation along KNP rivers is a concern to management. The TPC for invasion of the riparian zone by alien vegetation was defined as the rate of alien vegetation control being less than the rate of alien vegetation invasion. The resultant pragmatic model world for the alien vegetation TPC (Fig. vi) involves interactions between biological processes of alien vegetation, human resource availability KNP staff and utilization to clear aliens.

Although there is limited research and understanding of reedbeds (*Phragmites mauritianus*), the TPC for reed encroachment was defined as an increase in aerial extent of reeds beyond a predefined limit. The development of the reed TPC however, overlooked identifying the agents of system change. It is not clear what an increase in the aerial extent of reeds indicates. Reeds themselves, are likely to be important agents of change rather than indicators of agents of change. The utilisation of water by reeds (Birkhead *et al.*, 1997) or the influence on local biodiversity by reeds (van Coller, unpublished data) both imply that reeds are agents of change. Reeds are also considered to play an important role as physical ecosystem engineers, as they directly or indirectly control the availability of resources to other organisms by causing physical state changes in biotic or abiotic materials (Jones et al., 1997). Reeds alter their environment through increasing flow resistance which promotes increased sediment storage, thus altering geomorphology and vegetation succession. Given current understanding, we suggest that the reed TPC is inappropriate, and that alternative TPCs should be sought where indicators of reedbed expansion are used (e.g., species loss, alluvial bar development), rather than the reeds themselves. For this reason, neither the reed TPC nor its pragmatic model were pursued further in this project and should be critically reassessed by KNP management and researchers.

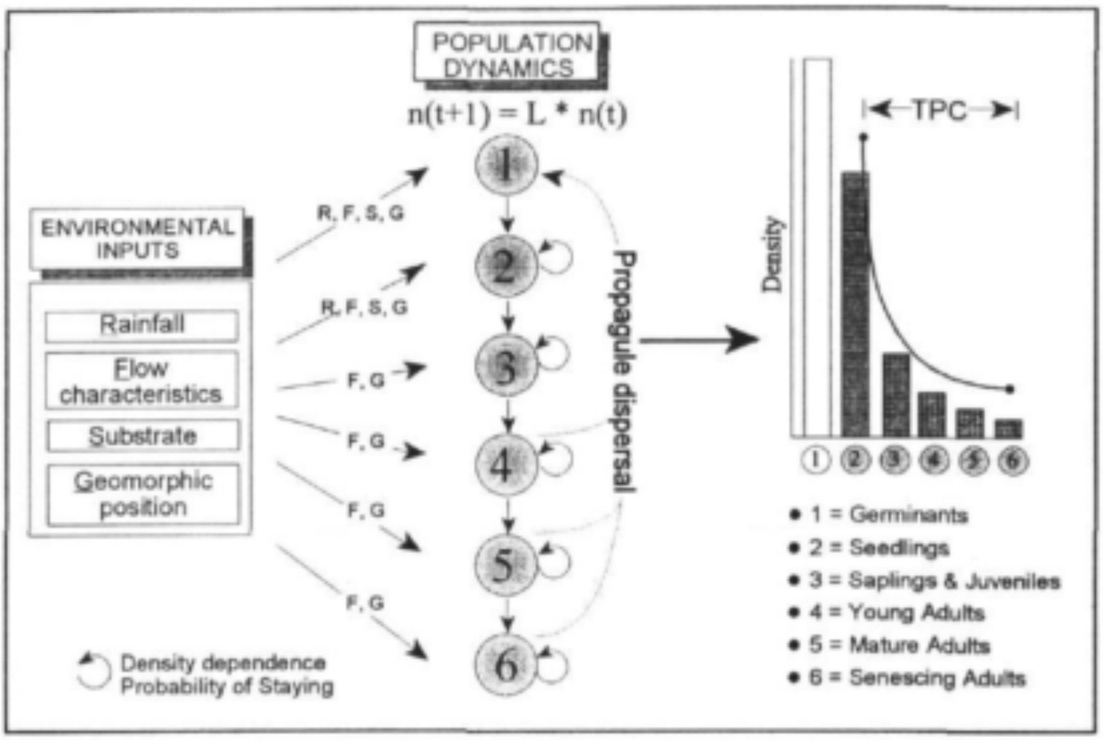

Figure v. Conceptualisation of the *Breonadia* pragmatic model world. The basis of the model is a population matrix model where the population (n) at time t + 1 is equal to the transition matrix multiplied by the population at time t. Density dependence and propagule dispersal are important feedback mechanisms. The output of the model is a population structure of non germinant individuals, from which the TPC may be assessed. (R=rainfall, F=flow characteristics, S=substrate, G=geomorphic position).

Table i. Hydrological states used in the *Breonadia* model.

Functional Flow Category	Inundation Frequency	Default Q ($m^3.s^{-1}$) values in the model
1. No Flow	-	0
2. Extreme Low Flows	active	0-1
3. Base Flows	active	1-5
4. Intermediate Flows	seasonal	5-20
5. High Flows	seasonal	20-120
6. Very Small Floods	ephemeral	120-300
7. Small Floods	ephemeral	300-500
8. Large Floods	ephemeral	500-2000
9. Catastrophic Floods	ephemeral	>2000

Converting the knowledge base into rules

The modelling approach adopted in this study is one of rule based models (*sensu* Starfield)withthe incorporation of matrix population modelling (Caswell, 1989), resulting in what has been termed a rule-enhanced model. In this instance, matrices in the riparian vegetation model have been constructed using size-structure categories to represent the tree population. Producing rules therefore involved the conversion of the knowledge base into functional states (of rainfall, hydrology and geomorphology), and meaningful rules. Rules took on the form of IF-THEN or ELSE type statements, which generate certain responses in the population structure depending on which environmental and vegetation conditions have been met. Relevant data were converted into rules which had both quantitative or qualitative elements, depending on the level of confidence in data analyses. Qualitative rules were especially useful in circumstances where data were lacking and where we had to rely on experience (expert opinion) and knowledge, or when there was a need to reduce complexity in the data matrix. Specific rules for the effects of

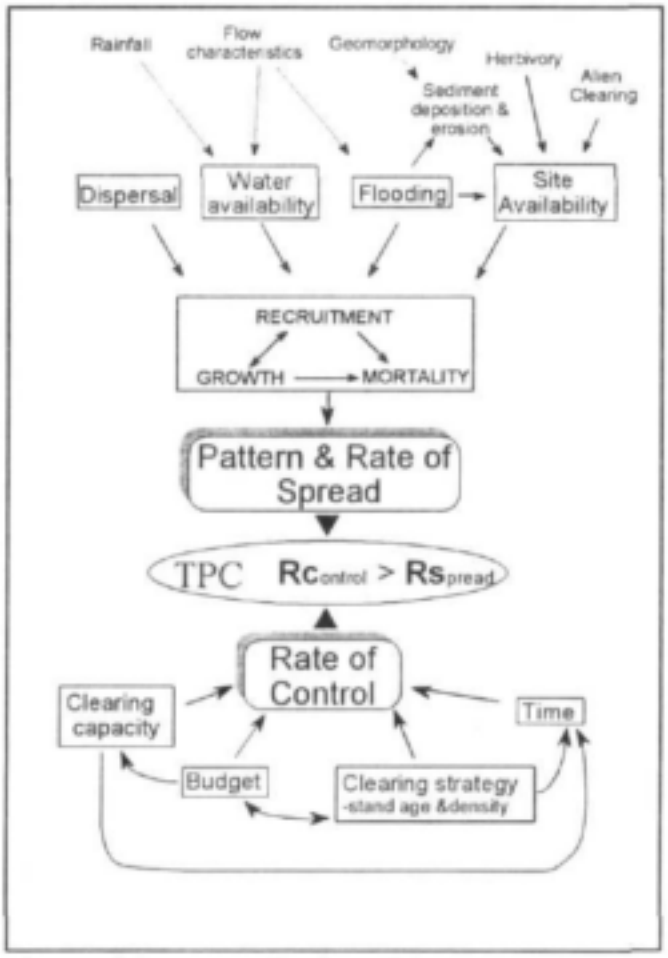

Figure vi Conceptualisation of the pragmatic model world for the alien vegetation TPC.

hydrology, geomorphology (substrate types), rainfall, size class longevity, fecundity, survival probabilities, the probability of staying in a size class or going to the next one, density dependence and population structure feedback were defined.

Designing the model engine

Designing the inference engine of the *Breonadia* model (Caswel, 1989) involved coding the rules, states, functions and procedures, and determining their sequence and manner of interaction. All coding was done in Visual Basic. Interaction between rules was important, especially the sequence and priority of different rules. A form of hierarchy was applied where it was necessary that certain rules have an overriding priority over others.

Rules are IF/THEN statements, that when strung together invoke a causal chain of reasoning to produce a particular outcome. IF/THEN statements can be composite where a number of AND statements are used in a rule statement to combine the influence of multiple factors. An example of a series of rules statements used in the matrix construction of the *Breonadia* model:

> IF Adult Density is High AND a Large Flood Event is False AND a Small Flood Event is False AND a Drought is False AND a NoFlow Event is False AND a Catastrophic Flood Event is False THEN
>
> In Row 1 and Column 6 of the matrix for actively flooded Mud/Silt = The Fecundity under no event conditions * 0.6./ (1 + (Starting population size) * Fecundity under no event conditions))
>
> ELSE IF Adult Density is High AND a NoFlow Event is True THEN
>
> In Row 1 and Column 6 of the matrix for actively flooded Mud/Silt = The Fecundity under NoFlow event conditions * 0.6./ (1 + (Starting population size) * Fecundity under NoFlow event conditions))
>
> ELSE IF etc.
>
> END IF

Producing auditable output

This involved up-dating explanation facilities in the model, with particular reference to changing default parameters, preparing input data, improving output confidence and interpretation, and auditing management goal achievement. Coding in Visual Basic means that the model is operated in the Windows environment. The advantage of this is a user-friendly interface that is also graphically pleasing. This was essential because model users were not involved in building the model. User interaction is increased because the model is event driven and not sequential, meaning that the user must select certain menus and engage certain options before events (such as data loading, data analyses, running, displaying outputs, saving outputs) occur. The model has good flexibility because the user is able to manipulate input data and parameters before running, and the outputs are graphically displayed, with options to view additional outputs or save them to disk. Output interpretation is made easy with explanations and explicit graphical indication of management goal achievement, i.e. TPC excedence is graphically shown alongside other model outputs.

Validating the model and evaluating the TPC

Model validation involved careful scrutiny of outputs to ensure that the model was responding correctly to the specific detail of each of the rules. Different scenarios were used to run the model to invoke all rules. Where necessary, corrections were made to the way rules were read and coded. Rules for fecundity, survival probabilities and probabilities of size classes remaining in the same size class, were tested in terms of their responses to hydrology and rainfall over 62 year periods. Validation resulted in several corrections to the model code and mechanism.

To evaluate the TPC, clear parameters were applied to the shape of the population structure curve (Fig. vi). Three parameters were selected:

- the degree of fit to the negative J-shape
- the slope of the curve (i.e., relative densities of smaller size classes to larger size classes)
- average densities of size classes (low densities indicate an unhealthy population)

To determine parameters, densities of different size classes were logged and linear regression applied to determine the degree of fit (r^2 value), the slope of the curve (x-coefficient), and average densities of population size classes (y intercept or constant). Thresholds for these parameters were defined by using the *Breonadia* model to provide first estimates from a scenario of declining bedrock and increasing loose coarse and fine alluvia, accompanied by progressively declining flow. The model was used because data to determine thresholds are inadequate. Threshold values are: $r^2 = 0.926$, x-coefficient = -0.68, and y intercept = 4.04.

If any of the three TPC parameters is exceeded in a particular year, then the TPC is also exceeded, but when using TPC excedence in decision support the following should be noted: Extreme events such as large and catastrophic floods and no-flow events cause an excedence of the TPC, with recovery occurring within 2 to 4 years. A sequential loss of exposed bedrock however, results in TPC excedence without recovery. This needs to be considered before management actions are taken as outlined in a formal protocol for using the TPC in decision support (Fig. vii).

Testing the model

Ideally, two sets of data collected at different times are required to test a model, with the second set being independent of those used in model development. The nature of this model however, would require that a set of data exists prior to and after key hydrological events and geomorphological changes. Not only do these kinds of data not exist, but they would take a long time to collect. Therefore, we tested the model using expert opinion and knowledge to verify acceptable model bahaviour (Starfield *et al.*, 1990). Different hydrological and geomorphological

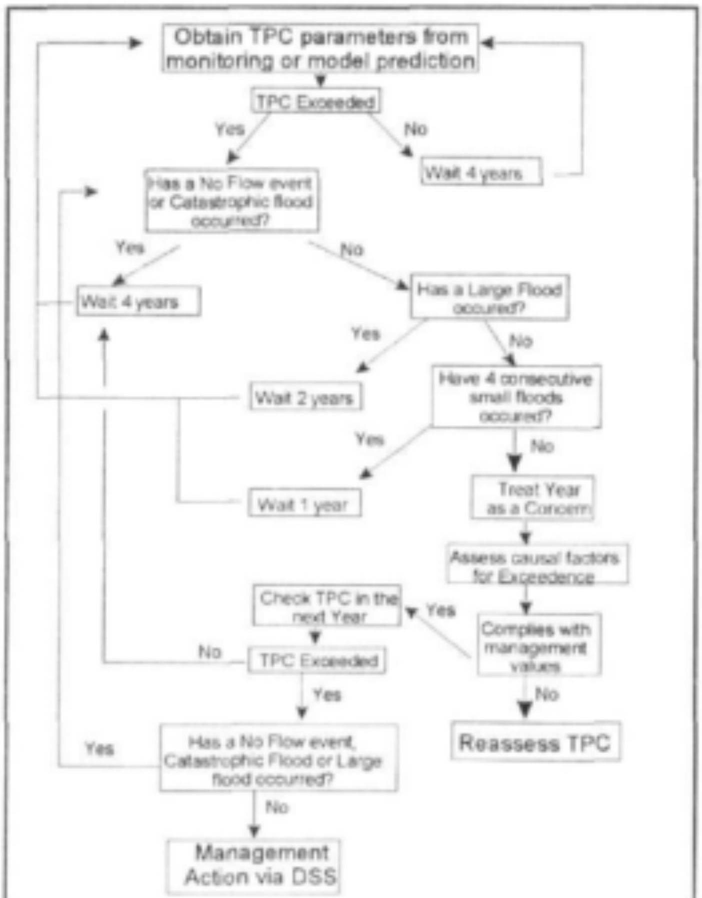

Figure vii. A formal protocol for the loss of bedrock influence TPC in the form of a decision tree.

scenarios were used in model runs of 62 years, and the outputs were assessed according to general trends over time and vegetation responses (all six biological classes) to extreme hydrological events and relevant and extreme geomorphological change. Results of model testing indicate that the developers are satisfied with model behaviour.

Conducting sensitivity analyses

A parameter sensitivity analysis was used to analyse uncertainty in the model. We used single parameter analyses by comparing the sensitivity index (S) between outputs from different model runs of 62 years. The sensitivity index is calculated from the model output (in this case population density for each of 6 classes) before and after the parameter change, as well as the values of the parameter being tested, before and after its change (Haefner, 1996), and is given by:

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

where R_a and R_n are model outputs i.e. 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. It was found that a negative and positive value (eg an S-value of 0.379 and -0.379) indicated equal levels of sensitivity.

The mean and range of all the sensitivity indices indicate that the smaller size classes are generally more sensitive than the larger size classes (Table ii). Within the smaller size classes, germinants and seedlings are more sensitive than saplings, while within the three groups of adults, mature adults are least sensitive in the model and senescent adults most sensitive.

Some extreme responses to parameter changes are notable in the sensitivity analyses. These all occur within the smaller size classes i.e. germinants, seedlings and saplings. Extreme responses to the elimination of catastrophic floods is due firstly to the extreme effect that catastrophic floods play in the model by reducing survival probabilities to zero, and secondly because the parameter change which results in catastrophic flood elimination is not a small one, thereby markedly increasing S.

Table ii. Summary of sensitivity analysis results for functional size classes of *Breonadia salicina*.

Biological Class	Sensitivity Index		Frequency of Occurrence of Sensitivity Index			
	Mean	Range	>=1	>=2	>=10	>=1000
Germinants	808175	439102903	11	10	6	6
Seedlings	520554	242455000	11	8	8	4
Saplings	24926	7093575	8	7	4	4
Young Adults	0.05	1.21	1	0	0	0
Mature Adults	0.05	1	1	0	0	0
Senescent Adults	0.07	1.762	7	0	0	0

Sensitivity analyses showed that there are three aspects that are important to managers for determining the response of *B. salicina*:

1. Hydrological states (flows) are the most important (highest S-values).
2. Substrate types are highlighted as being important, particularly exposed bedrock, firm alluvium and gravel.
3. *Breonadia salicina* population itself, particularly germinants, seedlings and saplings.

Development of a monitoring programme

The purpose of a monitoring program is to enable evaluation of achievement of defined management goals (TPCs). The model determines the type of data that need to be collected and the data can be used to further test and refine the model according to the defined limits of change:

1. Population density for all size classes
2. Daily rainfall
3. Daily discharge
4. Substrate proportion changes

Results from the sensitivity analyses have been used to prioritize monitoring efforts by focussing on the most sensitive parameters. Achievability of setting up a monitoring program needs to be weighed up against limitations of available resources, but results from the sensitivity analyses give an indication of monitoring reqirements (Table iii).

Table iii. Summary of monitoring requirements.

Motivation	Data Type	What to Sample	When to Sample	Where to Sample
ESSENTIAL DATA				
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

Development of a protocol for rule based modelling

Limited documentation of rule based modelling exists to guide the inexperienced modeler

(Starfield *et al.*, 1990), and while some example models focus on conservation and wildlife management, (Starfield & Bleloch, 1991) none of them are specific to riverine systems. A protocol was developed using the literature and the experience we gained. The protocol formalizes, with hindsight, the sequence of events and processes used for the development, testing and use of rule based models as decision support tools for river management. The protocol ensures that the principles of the experience and expertise gained from working on the Sabie River can be transferrable to other riverine systems in South Africa.

The protocol comprises a number of sequential steps and guidelines to developing a pragmatic rule based model. These steps are outlined in Fig. viii. The most important step is effective planning prior to the modelling exercise. The success of this critical step depends on recognizing the problem, defining the problem, defining management goals and defining objectives for the model that is to be developed. Once these are clearly defined and understood, modelling itself can begin.

Modelling starts with the conceptualization of the model components and the way in which they interact. The key to this phase is to constrain the number of model components and the complexity of interaction between them, with management goals. Building and coding the model is where rules are defined and coded so that the model is transformed from a conceptual framework to a working model. Rules are defined by both data analyses and expert opinion. It is important in this phase to choose a reliable and user-friendly interface, to embed explanatory notes into the model to aid its use, and to afford user control and flexibility in the model by not hard coding parameters, but making them adjustable by the user.

Only when the model is used, are previously unsuspected weaknesses in assumptions and in model formulation and accuracy revealed. Confidence in the model, therefore needs to be improved. This is done by validating and testing the model, and conducting a sensitivity analysis. Validating the model means making sure that the rules in the model produce the correct response according to their definition. The model is tested directly by comparing its output to newly collected or unused data, or indirectly by simply validating the model and checking the acceptability of its behaviour (Starfield *et al.*, 1990). A sensitivity analysis involves systematically changing model parameters, either uniformly or variably, to assess the sensitivity of model response to parameter changes

(Haefner, 1996). Results from the sensitivity analyses are used to further validate the model, design research strategies, indicate potential system controls, test theory and develop a monitoring programme.

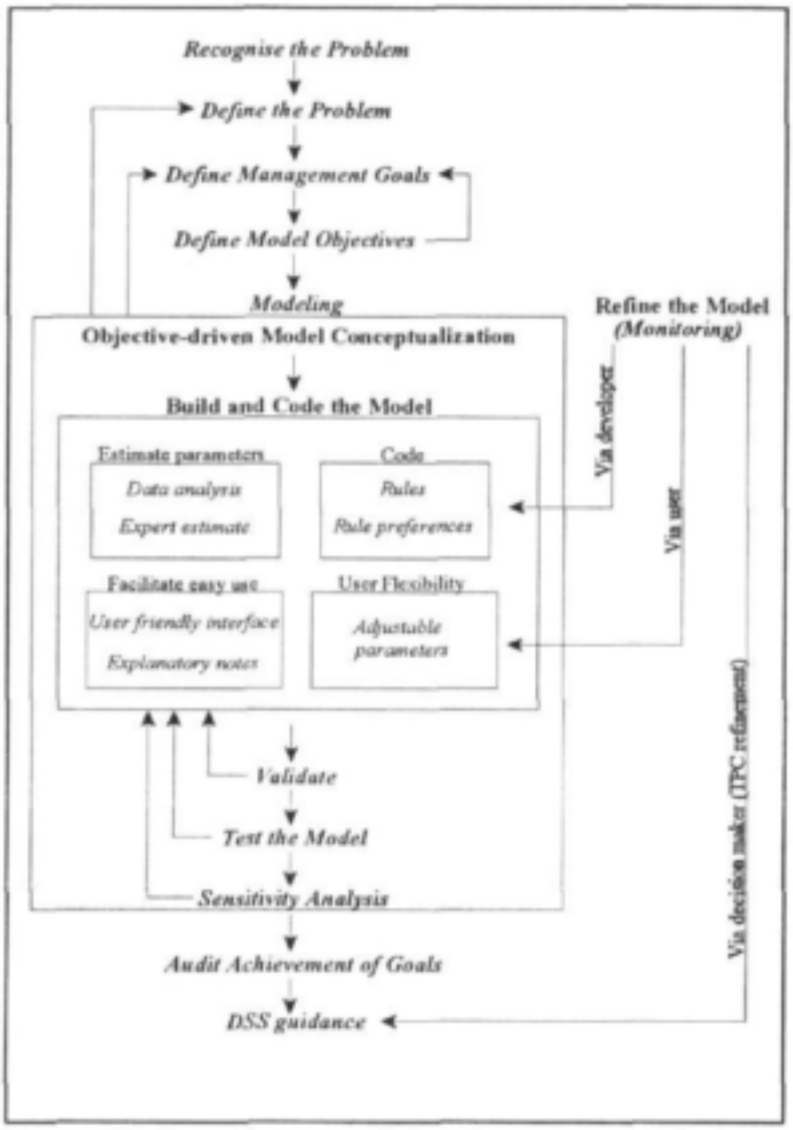

Figure viii. Flow diagram outlining the steps to developing rule based models as management tools.

Once the model is up and running it is then used to support and guide decision making. This is achieved by using the model to audit the achievement of management goals (e.g. TPC achievement) and then using the audit, together with model predictions of different management actions, as a support to the DSS. The model itself should be frequently subjected to refinement by users, developers and decision makers. Users can improve parameter estimates by updating model defaults using monitored data and research. Users also give feedback to developers who can refine rules and rule preferences, or incorporate additional rules into the model to address assumptions. Decision makers can also refine the model in that they can improve the critical values of the thresholds i.e. refine the TPCs. This will influence the outputs of auditing the achievement of goals as decision makers have essentially changed specific goals. The process of TPC refinement is well outlined by Rogers and Biggs (1999).

RESEARCH PRODUCTS

Research products resulting from this project are: Knowledge enhancement, a pragmatic rule based model, a structured monitoring programme, and a protocol for the development, testing and use of rule based models as decision support tools for river management. Target groups for these research products include: IFR assessments (DWA&F, Consultants), conservation and environmental management (Conservation / Environment Departments, Forestry), and river resource use policy formulation (Statutory bodies).

POTENTIAL APPLICATION OF RESEARCH PRODUCTS

1. Incorporation of riparian needs into IFR assessments (DWA&F, KNP, Consultants)
2. Conservation management of riparian systems (Conservation / environmental organisations, especially South African National Parks, Provincial Departments, Forestry)
3. As a base line against which to measure riparian system degradation and rehabilitation (Conservation agencies, environmental consultants, municipalities)
4. River resource use policy formulation (Statutory bodies)

RECOMMENDATIONS FOR FURTHER RESEARCH AND TECHNOLOGY TRANSFER

The model has certain assumptions which could be addressed in future research, and also several structural areas that need improvement to refine its accuracy and improve its usability. The most important recommendation for further research however, is to encourage links between this model and the ACRU model so that meaningful hydrological scenarios can be utilized to predict a response from riparian vegetation.

Technology transfer involves the transferal of the *Breonadia* model and the modelling approach (protocol) to potential users (especially KNP managers). A WRC project entitle "Rule based modelling of riparian vegetation and technology transfer to enable strategic adaptive management of Kruger National Park Rivers" has been approved. The general aim is 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. The first specific objective of this project is the transferal and implementation of the *Breonadia* rule based model to Kruger National Park management. The process of transferal will lead to adoption and a taking on of responsibility of the model.

Parameter changes to which the model is most sensitive were used to prioritise research efforts to improve confidence in their estimates. Accordingly, the following research efforts are recommended:

1. The correct and accurate definition in terms of discharge for catastrophic, large, and small floods, and base and intermediate flows needs to be formulated. This is because in the model, *B. salicina* is sensitive to floods and droughts, but the responses of *B. salicina* to high flows and very small floods needs to be investigated and rules for these interactions also included in the model (Table i).
2. Understanding of the nature and dynamics of germination (fecundity) following catastrophic floods needs to be improved.
3. The growth rates of *B. salicina* individuals need to be measured to establish a growth curve for the population which improves estimates of size class longevities and the probability of staying for each size class.
4. The influence of catastrophic and small floods on survival and growth rates needs to be investigated to improve estimates of catastrophic and small flood factors in the model.
5. The effects of rainfall on germinants, seedlings and saplings needs to be investigated to refine the rainfall rules in the model.
6. The nature of density dependence in *B. salicina* needs to be researched to improve the accuracy of its influence in the model.

Assumptions to be addressed by future research

A number of important assumptions are made within the model and need to be addressed through further research or monitoring:

1. **High flows (20-120 $m^3.s^{-1}$) and very small floods (120-300 $m^3.s^{-1}$) have no influence in the model, while extreme low flows (0-1 $m^3.s^{-1}$) to intermediate flows (5-20 $m^3.s^{-1}$) are only used to determine the occurrence of a drought event.** Data needs to be collected on the response (fecundity and survival) of the different size classes (especially germinants to saplings) to these lower hydrological states. Inclusion of these hydrological states as events in the model will greatly improve the accuracy of the model output.
2. **Growth rates are independent of substrate type and inundation frequency.** Measurement of growth rates of different size classes on different substrate types and flooding frequency levels are required to address this assumption.
3. **Drought and rainfall do not influence growth rate.** Growth rates of the different size classes need to be measured under no event, drought, and wet and dry rainfall years.
4. **Damage caused by flooding reduces growth rate of an individual.** Growth rates need to be measured before and after flooding events.
5. **Size classes cannot skip a size class (e.g germinants to saplings).** Growth rates of individuals need to be measured to determine whether size classes are ever skipped during a growing year.
6. **Density dependence is independent of substrate type and inundation frequency.** The self regulatory effect of density dependence on the different substrate types needs to be determined.
7. **All adult size classes have the same density dependence affecting their survival.** Differences in density dependence need to be determined for the range of adult size classes.
8. **Fecundity is independent of substrate type.** The number of germinants per adult needs to be determined on the different substrate types.
9. **All adult size classes have the same density dependence affecting their fecundity.** The effect of density dependence on fecundity would need to be compared between different adult size classes.
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).** The influence of

more than one hydrological event in a year on the *B. salicina* population would need to be measured.

11. **Herbivory does not influence the *B. salicina* population.** Exclosure plots would need to be set up to determine the influence of herbivory.
12. **Equal densities of the *B. salicina* population on different substrate types is assumed in the calculation of the vector matrix**. Densities on different substrate types need to be determined and built into the calculation of the vector matrix.

Structural improvements

1. The relative change in fecundity for different adult densities and between different size classes is hard coded. These values could be made adjustable to users
2. Not all input or output data are graphically displayed. The inclusion of a customizable graph will allow users flexibility to view various data and in other formats
3. The calculation of matrix eigen values and associated % changes in population density should be calculated and displayed. These have value to the interpretation of results as they indicate population fluxes
4. Graphical displays do not support more than 62 years
5. Rather than rule preferences where some hydrological rules dominate others, build in co-occurrence of rules with combined effects

CONCLUSION

The *Breonadia* model has value as a management tool because it:

- Predicts the population response of *B. 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 presentations of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.

Major management problems along the Sabie River are decreased flows and alluviation of the macro-channel. The *Breonadia* model predicts an unstable and 'unhealthy' population of *B. salicina* when flows and exposed bedrock proportions decline. The rate at which the population becomes a management concern depends on the rate of flow and bedrock reduction, and the exact values of TPC parameters. Prediction capability will be improved by improving hydrological and geomorphological interaction scenarios, and precise definitions of TPC parameter values.

Audits of the TPC are graphically presented with population size class density and input summaries, which enables interpretation of causes for TPC exceedence. This, together with a formal protocol to guide the use of TPC audits, effectively supports decision making. TPC exceedence objectively warns managers and decision makers of not achieving management goals, and prompts either TPC refinement or management action.

The future challenge for the *Breonadia* model is that it gets used and refined. Effective refinement will depend on post-use interaction between developers and users where users provide feedback of model operation and shortcomings. A proposal for the project entitled "Rule based modelling of riparian vegetation and technology transfer to enable strategic adaptive management of Kruger National Park Rivers" has been approved by Water Research Commission for commencement in 1999. Implementation of a suggested monitoring programme will provide necessary data with which to test and refine the model.

The *Breonadia* model is a predictive tool for management of the Sabie River, and was effectively developed in a data poor environment by taking a pragmatic rule based approach to modelling. The expertise gained from, and the approach used in this project are transferrable to other riparian systems. A protocol has been outlined that guides the application of a pragmatic rule based modelling approach. Guidelines are general, but illustrated by way of the example presented by this project.

The *Breonadia* model has three main targets: researchers, managers and policy makers. Researchers will use the model to highlight sensitive parameters and direct research efforts to improve the accuracy and reliability of model outputs and assumptions by improving the estimation of sensitive parameters. Model reliability and validation will also be improved by employing the proposed monitoring programme, so that the model can be tested against recorded data.

Managers will use the model to run TPC audits of scenarios of potential management actions, for example planting trees along the river, and scenarios of catchment developments, for example altered hydrological regimes due to dams, so that they can assess goal achievement under specified conditions. This will enable them to ascertain when to apply management actions, for how long, and to determine which actions might result in the maintenance of the desired state. Managers will also be in a better position to influence policy development and licenced allocations of the water resource by using model audits to justify the ecological Reserve.

Policy makers will not necessarily use the model, but they do exert marked influence on rivers and catchments. Policy makers can be shown with confidence, the justified requirements of conservation (the ecological Reserve), and it can be demonstrated to them, that prediction is achievable. When policy is then formulated it should be based on and incorporate, amongst other things, prediction.

In the KNPRRP context, and specifically in the Sabie River catchment, the *Breonadia* model, though specialized in its application, empowers conservation managers around the bargaining table of catchment role players. The model is essentially a river-section-scale tool (quantitative solicitation of a causal chain of our assumptions) that can be applied to catchment-scale decisions, actions or policy, by explicit definition, justification and consideration of the ecological Reserve for the Sabie River.

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LIST OF ACRONYMS

ACRU	Agricultural Catchments Research Unit
BLINKS	Biotic / Abiotic Links
CWE	Centre for Water in the Environment
DSS	Decision Support System
ICIS	Integrated Catchment Information System
IFR	Instream Flow Requirement
KNP	Kruger National Park
KNPRRP	Kruger National Park Rivers Research Programme

Chapter 1

INTRODUCTION

1.1 MOTIVATION AND RATIONALE

Legally, only one right to water is specified in the National Water Act; that of the Reserve (White Paper, 1997; National Water Act News, 1999). The Reserve consists of two parts:

- **The basic human needs Reserve**, which includes water for drinking, food preparation and personal hygiene.
- **The ecological Reserve,** which must be determined for all or part of any significant water resource such as rivers, streams, wetlands, lakes, estuaries and groundwater.

The Reserve must specify the quantity and quality of the water which will maintain the resource in an ecologically healthy condition and provide the basic human needs for water. All water uses under the National Water Act are subject to the requirements of the Reserve. Thus, licences for different types of water use cannot be issued without the Reserve having been determined.

Managers of a water resource are therefore faced with the task of determining the ecological Reserve in their area. All other uses of the water resource are then authorised according to the criteria of equitable allocations, beneficial use in the public interest, and promoting environmental values. These allocations are the responsibility of Catchment Management Agencies, in which conservation managers are usually involved. The difficulty of quantitatively justifying water demands for environmental use has weakened the bargaining power of conservation. Biologists and conservationists quantify water demands (justifiably so), with difficulty due to the complex nature of the systems they represent and manage and are therefore in need of tools such as the *Breonadia* model, that serve to quantitatively address the desired state (Rogers and Bestbier,

1997) of rivers in the catchment by being able to determine and justify the ecological Reserve.

In the Kruger National Park Rivers Research Programme (KNPRRP) context, and specifically in the Sabie River catchment, we have developed a model that, though specialized in its application, empowers the bargaining power of conservation managers around the table of catchment role players. The model is essentially a river-section-scale tool (quantitative solicitation of a causal chain of our assumptions) that can be applied to catchment-scale decisions or actions.

1.1.1 Background

Riparian vegetation plays a direct, key role in the functioning of river systems through its effects on water quality, hydrology (transpiration), hydrualics (flow resistance), sediment stabilisation and trophic processes (Rogers & van der Zel, 1989). Riparian systems are also major contributors to regional and global biodiversity (Naiman *et al.*, 1993) and provide many socio-cultural functions in the landscape (examples are soil fertility, food and building materials).

Studies on South African rivers are few (Rogers, 1995) and our ability to manage them according to their flow requirements is very limited. In particular we lack the ability to predict a response of riparian vegetation to changes in flow and geomorphology, the two primary determinants of riparian vegetation structure and composition. This lack of capacity is largely due to data and understanding limitations, and therefore very few models have been developed. However, models help us make decisions despite the lack of data and understanding, help us improve our understanding, and indicate which data we need to collect (Starfield, 1997).

Studies on the Sabie River (van Coller, 1993; van Niekerk & Heritage, 1993; Chesire, 1994; Carter & Rogers, 1995; de Fontain & Rogers, 1995; Heritage *et al.*, 1997; van Coller & Rogers, 1995, 1996; Birkhead *et al.*, 1997; Mackenzie, unpublished data) provide the current data base to develop management and predictive capabilities. A prototype predictive model of the response of riparian vegetation to flow and geomorphological change in the Sabie River was developed by the CWE in conjunction with the Civil Engineering department of Stellenbosch (Jewitt *et al.*, 1998) under the auspices of the KNPRRP (Breen *et al.*, 1994). The time scale for this study was limited and did not allow for adequate model development. In particular, the response of riparian vegetation to hydrological events such as droughts and floods was not incorporated. There is therefore the need and opportunity to further develop and improve the prototype riparian vegetation model to include response type data such as rainfall, hydrological discharge, substrate dynamics and pre-existing vegetation densities, as well as improve its support of the management process and user friendliness.

1.1.2 Application to the KNPRRP

The potential value of the prototype riparian vegetation abiotic/biotic links (BLINKS) model as a predictive management tool for the Decision Support System of the KNPRRP, needed to be carefully evaluated if its full potential was to be realised. Such an evaluation provided a basis for highlighting modelling, knowledge and research needs.

Kruger National Park staff and associated institutions have also recently defined goals for river conservation (Rogers & Bestbier, 1997) which can be used to better focus the second generation model construction and output in an iterative process of prediction and goal refinement.

Construction of the Injaka dam on a major tributary of the Sabie River (Marite), further development of land in the catchment, increased water abstraction from the Sabie, and changes in the Kruger Parks elephant management policy, all increase the urgency for formulation of an efficient predictive model and monitoring programme to audit achievement of management goals.

1.1.3 Transferability of expertise to other rivers

While the Sabie River provided a useful and sensible study site for this project, it is imperative that the expertise developed be extended beyond the KNPRRP as the second objective of that programme requires (Breen *et al.*, 1994).

One means of ensuring better transfer of predictive capability and modelling expertise to the broader community is to develop a set of guidelines which explains the steps to be taken in developing, testing and using such models. A procedure for obtaining a useful knowledge base which is then implemented in a rule based model needs to be outlined. In addition, procedures for rule based modelling and the philosophy behind this approach are not outlined in the literature.

There is therefore a need to formalise an approach to studies aimed at developing and using predictive rule based models, especially as management tools. Experience gained from this project was therefore used to develop a generic protocol that will assist and guide researchers and managers in the future.

1.2 AIMS AND OBJECTIVES

The overall aim of this project is to improve the national potential to manage the response of riparian systems to changes in flow regime and geomorphology. In order to achieve this aim the following specific objectives were pursued:

i. Evaluate the riparian vegetation abiotic/biotic links model of the Sabie River that was developed by the KNPRRP to ascertain additional knowledge and data needs for improved decision support.

ii. In the light of this evaluation, improve the knowledge base by assessing the response of vegetation and geomorphology of the Sabie River to the recent severe droughts (1992 & 1995) and floods (1996).

iii. Refine or if necessary redesign the 1996 prototype riparian abiotic/biotic links model in order to address specific management goals.

iv. Develop a monitoring programme for evaluation of achievement of riparian management goals for the Sabie River.

v. Produce a protocol for the development, testing and use of rule based models as decision support tools for river management.

These objectives are not in any order of priority, but are in a sequence which allowed an incremental and iterative approach to their achievement.

1.3 STUDY AREA

1.3.1 Catchment Characteristics

The catchment of the Sabie River is situated in the Mpumalanga region of South Africa and the southern lowland region of Mozambique and has an area of 7096 km^2, of which 6347 km^2 are within South Africa (Chunnet &Fourie, 1990) (Figure 1.1). The Sabie River originates at an altitude of 2200m on the Drakensberg escarpment, and flows eastwards for 210 km to its confluence with the Inkomatie River in Mozambique. The section of river under study falls within the lowveld zone, where the gradient is low, and extends for 106 km from the western boundary to the eastern boundary of the KNP.

The human population within the Sabie River catchment is expected to increase from estimates of 338000 people in 1985 to about 691000 people by the year 2010. In 1985, approximately

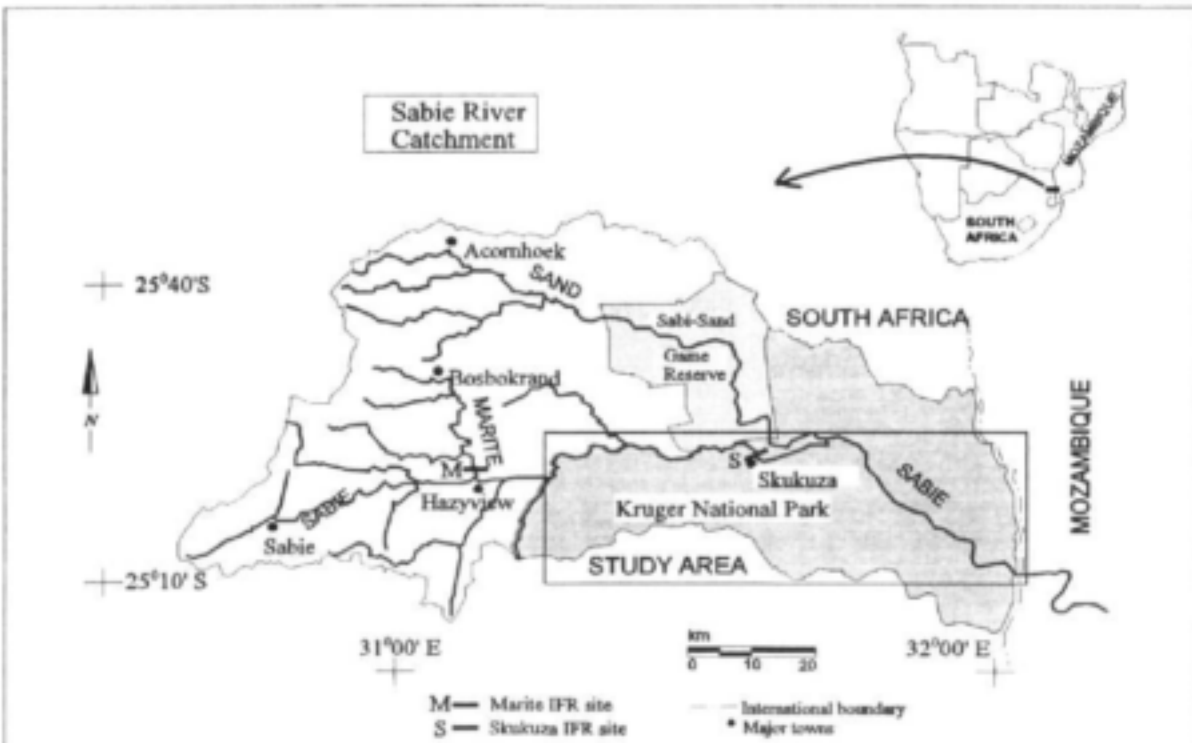

Figure 1.1. Location map showing the study area: the Sabie River and its catchment.

80000 people outside the Sabie catchment boundaries were also dependent on its water, and it is estimated that this number of people will increase to 166000 by the year 2010 (Chunnet &

Fourie, 1990).

1.3.2 Geology and Geomorphology

The geology through which the Sabie River flows is diverse and complex and has been described in detail by Chesire (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 what a macro-channel with of relatively steep stable banks either side of the more dynamic macro-channel floor (Figure 1.2).

The Sabie River has been described as a mixed bedrock-alluvial system displaying characteristics of both bedrock and alluvial influence. Five principal channel types have been identified; single,

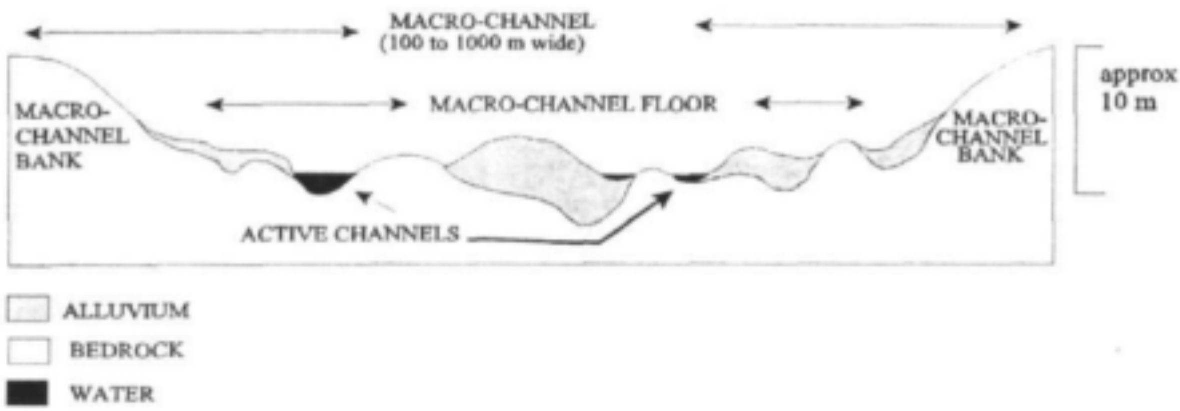

Figure 1.2. Schematic diagram showing a cross section through the Sabie River. The macro-channel is composed of the macro-channel bank and the macro-channel floor.

pool-rapid, braided, bedrock anastomosing and mixed anastomosing. 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 & Heritage, 1994; Wadeson & Rowntree, 1995; Donald *et al.*, 1995).

1.3.3 Climate and Hydrology

The region is characterised by a semi-arid to sub-tropical climate. There is a gradient of decreasing rainfall from west (1800-200 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. 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 (Chiew & McMahon, 1995) and flooding is closely associated with summer rainfall in the form of thunderstorms. 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 as far back as 1932 (Chunnet & Fourie, 1990). Recently the Sabie River has experienced a severe drought (1992) and a flood (1996) of approximately 1 in 50 year return period, 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 & Fourie, 1990), and the construction of the Inyaka dam on the Marite River (a major tributary of the Sabie), will further alter the natural flow regime. The dam will also mean an increased potential to manage flow, albeit at small scale.

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. Managers of the Sabie River, therefore understand the need to conserve bedrock influence in the system in order to fully meet their objectives and goals.

1.3.4 Vegetation

Vegetation along the Sabie River within the KNP has been described in detail by Bredenkamp and van Rooyen (1991) 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.

A vegetation type refers to a suite of species that have similar distribution patterns. The term 'vegetation type' is comparable to vegetation community, but with vegetation types occurring 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 are named according to the dominant species: *Phragmites mauritianus* reed vegetation, *Phyllanthus reticulatus* shrub vegetation, *Combretum erythophyllum* 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 the geomorphology where the latter two occur on the macro-channel bank, and the former four occur on the macro-channel floor.

1.4 MANAGEMENT ISSUES

The Kruger National Park Rivers Research Programme (KNPRRP) promoted interactions between stakeholders, managers and researchers. This was facilitated by a decision support system (DSS) which provided a technological interface between management and research (Rogers & Bestbier, 1997). Through the DSS, a description of the desired state of the rivers on the KNP was set in such a way that it could be translated into operational goals that were also auditable in terms of achieving the desired state (Rogers & Bestbier, 1997). In setting conservation goals, attention was focussed on establishing functional Thresholds of Probable Concern (TPCs) and an effective monitoring programme to help audit their achievement. A fundamental component of the management process is a predictive modelling framework that is able to predict the consequences of management actions for the achievement of conservation goals (TPCs) (Rogers & Bestbier, 1997; Rogers & Biggs, 1999) (Fig. 5.1). It is within the modelling framework that predictive tools such as rule based models are utilized, and where models directly incorporate management goals, they effectively become predictive management tools.

Chapter 2

LITERATURE SURVEY

2.1 MANAGEMENT ORIENTATED MODELLING

Conservation managers operate in multidimensional decision making environments that demand innovative management approaches and achievable, auditable goals (Bestbier *et al.*, 1996). It is generally accepted that there is a lack of coordinated effort to understand and manage riparian corridors in southern Africa (Rogers & Naiman, 1997). Projects such as "Modelling abiotic-biotic links in the Sabie River" (Jewitt *et al.*, 1998) arose because managers in the KNP realised that research products of the KNPRRP were not adequately addressing the biotic/abiotic links in riparian systems, even though an objective of this programme was to predict the biological consequences of changes to the river (Breen *et al.*, 1994).

2.1.1 Why use models?

Models have been defined in different ways. Jeffers (1982) has called them formal expressions of the relationship between defined entities in physical or mathematical terms. Brown and Rothery (1994) see them as simplified representations, which are designed to facilitate prediction and calculation, and which can be expressed symbolically or mathematically. Models are essentially representations or abstractions of systems or processes (Starfield & 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, which are not mutually exclusive, (such as deterministic, stochastic, descriptive, mechanistic, dynamic, non-dynamic, computer, matrix, qualitative, quantitative, rule based, frame based, and word models, to name but a few) but all models function to explore what we believe to be true.

Clearly, modelling has a place in a programme such as the KNPRRP, but modelling is a broad field and some approaches will deal with present resource constraints and address the objectives of the programme better than others.

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. Other modelling techniques such as rule based modelling (Starfield & Bleloch, 1991) have arisen where the modelling approach de-emphasises the necessity for complex mathematics, and enables the development of dynamic, deterministic models in situations where data are sparse or absent. 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 & James, 1995), and can indicate which types of data are best to collect to improve confidence in predictions.

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 (even without data) and management actions.

2.1.2 A pragmatic approach to modelling

Adaptive management is a widely accepted paradigm in natural resource conservation, but many problems limit its implimentation (Walters, 1997; Baskerville, 1997). Rogers, (1998) suggests that divergent operational philosophies are the fundamental reason for poor communication and interaction between scientists and managers. Scientists are inclined to solve intellectual problems irrespective of their usefulness, while managers solve problems pragmatically (Rogers, 1998). While each group is justified in their approach, they need to find commonality in process and purpose if interaction between them is to be effective (Rogers, 1998). We have utilized the products of scientific research in a pragmatic modelling approach (Starfield, 1997), which ensures our predictive tool is both scientifically sound and management proficient.

Starfield (1997) poses the question "Good managers make good decisions, but what constitutes a good decision-making process?" A good process is logical and defensible, with three essential steps for making decisions:

- Clearly define and understand the objective,
- Measure the extent to which a solution or strategy meets the objective, and
- Rank alternative options or strategies in terms of the measured extent to which a solution or strategy has met the objective.

The implementation of these three steps in the development of the current riparian vegetation model (*Breonadia* model) is demonstrated in subsequent chapters. There are seven common misconceptions about developing models that impede their use (Starfield, 1997):

- The development of a model requires a complete understanding of the behaviour of the system or population that is being modelled
- Models that are developed using incomplete data sets are not useful, so it is better to collect all the data you are likely to need first
- Models that have not been validated, tested or proven to be accurate in their predictions, are not useful in any way
- Biological models must be as detailed as possible, so that all the system processes and dynamics are included
- The process of modelling is too difficult for most managers and field biologists to understand
- The primary purpose of developing models is to make predictions
- Modelling is time-consuming and expensive, so develop multipurpose models while you are about it.

These misconceptions are rooted in the assumption that models accurately describe reality, and can therefore be considered as representing the truth. 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". Each of the misconceptions listed above is addressed by a pragmatic approach to modelling:

- Managers have to make decisions, and in ecological situations they mostly do so without a complete understanding of the systems they manage. This is where pragmatic models (defined as hypotheses) are particularly useful in aiding decision making because they represent our best understanding and predict consequences in light of this understanding. It is critical however, that the assumptions of the model (and our understanding) are explicitly considered in interpretation of predictions and that the model is treated as a hypthesis in need of testing in an adaptive management process.
- Even with incomplete data sets, a model can indicate how sensitive it is to missing data. If models are being used to evaluate alternative management options for example, some of the options might be insensitive to missing data, while others, if they are sensitive, will indicate which data to collect.
- Validation of a model is crucial if the model is a "truthful representation" of reality, but pragmatic models (tools, experiments or hypotheses) reveal the logical consequences of their assumptions. Validation is therefore less important in pragmatic models, but it remains extremely important to justify assumptions, ensure internal consistency in the model, and utilize and interpret outputs sensibly (Oreskes *et al.*, 1994) in an adaptive management approach.
- Pragmatic models are developed for specific purposes and are therefore most effective when they contain only as much detail as is necessary to perform their predefined tasks. Additional detail makes them less user friendly and does not necessarily enhance the level of confidence in their predictions.
- Using a model as a problem-solving tool requires that its users understand it. This is where having only relevant detail also pays off. The ability to understand the model is increased and users can become involved in the mechanism of the model instead of simply feeding it input to get output.
- Pragmatic models often only make forecasts or projections rather than predictions, and understanding their mechanism can have as much value as interpreting their outputs.
- Clearly if models are defined as problem-solving tools then they do not have to be large

multipurpose models that attempt to answers numerous questions. In fact, the most notable feature of pragmatic modelling is that it produces a suite of small, single-purpose models rather than a few, large, multipurpose models.

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 will demonstrate in this project that the pragmatic model we developed deals with uncertainty, lending itself to improvement by users, while still meeting its objective. The current model began as a qualitative rule based model as part of the BLINKS project (Jewitt *et al.*, 1998) and its refinement is reported here.

It is first necessary to briefly review the literature concerning riparian vegetation dynamics, and especially those associated with hydrology and geomorphology. In the absence of data, this forms the information base from which rules in the *Breonadia* model were defined.

2.2 A DEFINITION OF THE TERM RIPARIAN

It is critical when undertaking any study to know the domain within which one is operating (Pickett *et al.*, 1994). The term 'riparian' is most commonly used in the context of riparian zone (Swanson *et al.*, 1982; Gregory *et al.*, 1991; Naiman & Décamps, 1997) or riparian corridor (Naiman *et al.*, 1993; Naiman & Pollack, 1993; Rogers & 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 (Kolvachick & Chitwood, 1990; Gregory *et al.*, 1991). This zone of transition between these two ecosystems is what is known as an ecotone (Décamps & 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, 94).

Despite an initial impression of riparian corridors being recognisable from a distance, they are nevertheless difficult to delineate (Gregory *at al.*, 1991). In fact, views differ markedly as to the lateral and vertical extent of the corridor. These differing spatial extents are defined in relation to the type and temporal nature of the hydrogeomorphic processes. In this study we adopt the definition in its broadest sense which refers to stream channel and that 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). This therefore incorporates that 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 &Brown, 1992). Adopting the broadest definition of the term riparian, the lateral and vertical extent of the Sabie River riparian zone includes that area within the confines of the macro-channel extending to the top of each bank, since this is the outward limit of flooding (Fig. 1.2).

2.3 RELATIONSHIPS BETWEEN VEGETATION, GEOMORPHOLOGY AND HYDROLOGY

Hydrological and fluvial processes are key determinants of vegetation distribution patterns in riparian corridors (Swanson *et al.*, 1982; Harris, 1988; Rogers & van der Zel, 1989; Kovalchik & Chitwood, 1990; Stromberg *et al.*, 1991, 1993; Hupp & Osterkamp, 1996). Vegetation is influenced by the hydrology of the river through floods, droughts and water table fluctuations, while fluvial processes of erosion and sedimentation both destroy and create sites for establishment of new individuals (McBride & Strahan, 1984; Cordes *et al.*, 1997).

2.3.1 Flooding

Flooding directly affects plants by inundation, physical damage or uprooting of individuals, resulting in reduced growth or even mortality (Gill, 1970; Frye & Quinn, 1979; Swanson *et al.*, 1982; Rogers & van der Zel, 1989; Stromberg *et al.*, 1991, 1993). Species differ substantially in their ability to tolerate these affects of flooding (Blom *et al.*, 1990), which are reflected in different species distributions along a flooding frequency gradient (Auble *et al.*, 1994). Species close to the channel are predominantly hydrualically tolerant (i.e. able to survive the physical stress of flooding), while species on higher elevated sites, the top of banks or upland areas, are generally hydraulically intolerant and hydrologically influenced (benefit from water in the water table or mesic sites for regeneration following a major flood).

Many factors influence the recruitment of plants (Grubb, 1977; McBride & Strahan, 1984; Cordes *et al.*, 1997), but the influence of flooding is particularly important during the regeneration phase of riparian plant populations, because flooding has the potential to alter the seedling layer and thus opportunities for canopy replacement (Streng *et al.*, 1989). In the more humid areas of North America, establishment of floodplain forests depends on site availability and availability of viable seeds (or propagules) with low water levels during the germination and establishment stages (Streng *et al.*, 1989). Flooding tolerance and soil moisture thus act selectively to determine seedling success on newly available sites during the growing season (Hughes, 1994). In semi-arid areas, sites are often more abundant, but water availability is a limiting factor (Hughes, 1988). In North America, studies on Poplars have indicated that flooding is particularly important in providing suitably moist sites for regeneration and tolerance to flooding is viewed as being less important (Hughes, 1994).

Since flooding plays a key role during germination and establishment, the phenology of plant species relative to the timing of floods becomes important (Tissue & Wright, 1995; Mackenzie, unpublished data). In semi-arid regions, if plant species are to regenerate successfully following flood events, seed or propagule dispersal must coincide with floods. Along the Sabie River, this is generally the case, but more so for species growing along seasonally and ephemerally flooded features. The viability of seeds and propagules of riparian species is generally low and few form seed banks . Thus, dispersal of seeds or propagules too soon before, or too late after, a flood event will result in missed opportunities for regeneration.

2.3.2 Water Availability

Fluctuations in the groundwater table in river banks are 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 species which 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 & Rogers, 1996).

The depth to the water table becomes 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 & 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 have some complexity to this general rule however, because the presence of bedrock control influences the dynamics and structure of the water table. Perched water tables which need to be recharged by flooding events often exist.

2.3.3 Fluvial geomorphology

Fluvial geomorphic processes (cycles of aggradation and degradation) give rise to a highly complex mosaic of landform patches at different spatial and temporal scales (Hupp & Osterkamp, 1996). Close relationships exist between riparian vegetation distribution patterns and different geomorphic landforms (van Coller *et al.*, 1997). In more humid areas, flooding frequency associated with each landform is regarded to be the process underlying observed relationships between vegetation and different landforms, and not influence of the landform per se (Hupp & Osterkamp, 1985, 1996). In semi-arid regions, the relationship is related more to infrequent flood events that create new sites for the establishment of individuals (Friedman *et al.*, 1996). Therefore in riparian corridors in semi-arid areas, the vegetation / geomorphology interactions are more event driven, and flow frequency associated with the different landforms is less important. The implication for this study was that more emphasis was placed on event driven rules than rules relating to flow frequency, although both exist and interact 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 as a result of land degradation in the catchment may increase sediment storage in the river which will in turn alter the degree of bedrock influence in the model. A reduced bedrock influence is predicted to result in a decrease in the extent of certain vegetation types (the *B. salicina* vegetation type), while other vegetation types may increase (the *Combretum erythrophyllum* vegetation type) (van Coller *et al.*, 1997).

Feedback mechanisms of riparian vegetation on fluvial geomorphology exist, which contribute to the relationship between them (Hicken, 1984). Vegetation can exert considerable control over fluvial processes and morphology through five mechanisms: flow resistance, bar sedimentation, bank strength and stabilization, and the formation of log jams.

2.4 IMPACTS OF FLOW REGULATION BY DAMS ON RIPARIAN CORRIDORS

The construction of a dam on a major tributary of the Sabie River, the Marite River, necessitates a brief literature survey of the impacts of dams on riparian corridors. The main impacts of dam construction are: decreased flow volumes (and related attributes of water table recharge and floodplain soil wetting), deceased frequency and magnitude of flooding, altered timing of flooding, reduced variability in hydrological regimes, and usually decreased sediment loads (Hughes, 1994). All these attributes have the potential to dramatically alter both the fluvial geomorphology and riparian vegetation characteristics (abundance, composition and distribution).

A marked reduction in riparian vegetation abundance follows flow regulation by dams, especially in semi-arid regions (Rood & Mahoney, 1990; Stromberg, 1993; BenDavid-Novak & Schick, 1997). This decline has been attributed to a reduction in regeneration following attenuation of spring flooding, reduction in sediment deposition, bank stabilisation and an increase in drought stress on older individuals (Rood & Mahoney, 1990). Many trees died along the Sabie River during the extreme drought in 1992 (van Coller & Rogers, 1996). In more humid temperate regions however, riparian vegetation abundance has been found to increase with flow regulation (Johnson, 1994). This is a result of active sites becoming available for colonisation in response to reduced summer flows, so that channels become narrower and the extent of the riparian vegetation increases. This process was found to stabilize over time however.

Flow regulation may also reduce species richness (Nilsson & Janson, 1995). The composition of the vegetation may also change, as species more characteristic of upland, non flooded areas, increase in abundance (Thomas, 1996). Alteration of the timing of peak flows is likely to favour different species due to differences in phenology, thus influencing their regeneration potential.

Chapter 3

APPROACH AND METHODS

The approach and methods for this study are presented for each of the five objectives outlined in the first chapter.

3.1 EVALUATION OF THE EXISTING PROTOTYPE RIPARIAN VEGETATION BLINKS MODEL

The existing BLINKS riparian vegetation model described in the previous chapter was iteratively evaluated in terms of:

1. Model constraints and assumptions to determine how best to improve confidence in the output.
2. The extent to which the existing knowledge base has been used and the potential for incorporation of additional existing knowledge and data.
3. The potential to provide decision support for management and to define research to improve decision support.
4. Parsimony of model structure and use and ability of model to generate auditable output.

More detailed methods for the evaluation of the BLINKS riparian vegetation model are presented together with the outcome in the next chapter.

3.2 IMPROVING THE KNOWLEDGE BASE AND PREDICTING A VEGETATION RESPONSE

This exercise was aimed primarily at capturing the response of riparian vegetation to events such as droughts and floods, which the prototype BLINKS riparian vegetation model could not incorporate. In semi-arid systems, riparian corridors are influenced to a large degree by infrequent severe droughts or failed wet seasons and infrequent large magnitude floods (i.e., an event driven system). An extreme drought during the wet season of 1992/1993 resulted in the death of numerous riparian trees (van Coller & Rogers, 1996). A few years later in February 1996 a flood, with an estimated one in fifty year return period, occurred along the Sabie River. Within a relatively short period there was therefore the opportunity to collect information on the response of riparian vegetation to both kinds of events.

The precise methods used to collect the necessary information and data on these drought and flood events depended largely on the outcome of the evaluation of the prototype model. Data on vegetation response to the flood were collected at the species and landscape type (rock, sand, reeds and shrubs, shrubs, and trees) levels. Existing surveyed transects originally sampled in 1990, were re-sampled at the end of 1996 to determine the extent of loss, death and damage of individuals as a result of the flood. A comparative analysis of a set of aerial photographs taken before (1986) and after (1996) the flood was undertaken to determine the changes in landscape states. Grids with cells equivalent to 20 x 20 m on the ground were used to analyse the change in landscape states. Geomorphological change was also recorded at the morphological unit scale.

Vegetation response to the drought was recorded in two ways. Firstly, an aerial census from a helicopter was undertaken along the Sabie River from the western to the eastern boundary to determine the overall extent of mortality due to drought. Species and numbers of individuals that had died (noted by a lack of leaves and loss of bark) were recorded in relation to their distance downstream, from which the relationship of mortality with channel type could be established. Secondly, a ground census was undertaken where mortality and degree of stress were recorded on existing surveyed transects. This enabled a relationship between mortality and stress to be established with elevation above, and horizontal distance away from the channel, discharge (determined from existing stage discharge relationships for each transect), and morphological units.

This improved knowledge base provided vital information and data for the refinement of the riparian vegetation model.

3.3 REFINEMENT AND DEVELOPMENT OF THE MODEL

Seven steps were iteratively undertaken in refinement and development of the riparian vegetation model, and are generally discussed in this chapter. Detail is presented in subsequent relevant chapters.

3.3.1 Redesign the conceptual models to define the problem and model objectives

It is essential when developing any model that the problem being modelled, or the model objective is clearly defined (Starfield, 1997; Starfield & Bleloch, 1991; Starfield *et al.*, 1990). The design and development of the model depends on its objective. Conceptual models of the problems being modelled were therefore developed to help focus the model development. A conceptual model of riparian vegetation dynamics was also developed to facilitate the identification of the driving factors behind change in vegetation composition and structure. A refined and simplified conceptual model, specific to the problems, was developed by combining a conceptual model of the problems with that of the vegetation dynamics conceptual model. This considerably reduced the complexity of the original vegetation dynamics conceptual model by eliminating irrelevant detail. Subsequent model development was then guided by this simplified and relevant conceptualization (problems and objectives), which resulted in a compact and pragmatic model. Additional detail is discussed in chapter 5.

3.3.2 Convert the knowledge base into rules

The modelling approach adopted in this study is one of rule based models (*sensu* Starfield) with the incorporation of matrix population modelling (Caswell, 1989), resulting in what has been termed by some, a rule-enhanced model. In this instance, matrices in the riparian vegetation model were constructed using size-structure categories. Producing rules therefore involved the conversion of the knowledge base into functional states and meaningful rules. Rules in the model took on the form of IF-THEN or ELSE type statements, which apply certain responses depending on which of the conditions have been met. Relevant data were converted into rules which had both quantitative or qualitative elements to them, depending on the level of confidence in data analysis. Qualitative rules were especially useful in circumstances where data were lacking and experience (expert opinion) and knowledge had to be relied on, or when complexity in the data matrix needed to be reduced. Refer to chapter 6 for additional detail.

3.3.3 Design the inference engine of the model

Designing of the inference engine of this standard stage class model (Caswel, 1989) involved coding the rules, states, functions and procedures, all of which was coded in Visual Basic. Interaction between rules was important, especially the sequence and priority of different rules. A form of hierarchy was therefore applied to the rules where it was necessary that certain rules have an overriding priority over other rules. The various assumptions inherent in rules and the model were recorded. Chapter 6 provides detail of the structure of the model.

3.3.4 Convert model into auditable output

This involved up-dating explanation facilities in the model, with particular reference to changing default parameters, preparing input data, improving output confidence and interpretation and auditing management goal achievement. Coding was in Visual Basic which means that the model is operated and runs in the Windows environment. The advantage of this is ease of use due to a user friendly interface that is also graphically pleasing, which was essential because users of the model (essentially managers) were not involved in building the model. User interaction is increased because the model is event driven and not sequential, meaning that the user must select certain items and click certain menus and buttons before events (such as data loading, data analysis, running, displaying outputs, saving outputs) occur. The model has increased flexibility because the user is able to manipulate input data and parameters before running, and the outputs are graphically displayed, with options to view additional outputs or save them to disk. Output interpretation is made easy with explanations and explicit graphical indication of management goal achievement.

3.3.5 Model validation and TPC evaluation

Model validation involved careful scrutiny of outputs. Different scenarios were used to run the model so that all types of rules were invoked. Outputs were then analysed to make sure that the model was responding correctly to the specific detail of each of the rules. Where necessary, corrections were made to the way rules were read and coded. The results of the model validation are discussed in greater detail in chapter 7.

Thresholds of Probable Concern were evaluated by running the model with different hydrological and geomorphological scenarios for 62 years, and assessing the modeled state of the system relative to the TPC over time. TPC parameters indicate either an acceptance of change within the threshold, or an excedence of the threshold due to change. TPC parameters were defined using the model in this way, and quantitative values were set for the thresholds. Chapter 7 describes the details of the evaluation.

3.3.6 Testing the model

Ideally, two sets of data collected at different times are required to test a model, with the second set being independent of those used in model development. The nature of this model however, requires that a set of data exists prior to and after key hydrological events and geomorphological changes. Not only do these kinds of data not exist, but they would take a long time to collect. Therefore, we tested the model using expert opinion and knowledge. Different hydrological and geomorphological scenarios were used in model runs of 62 years, and the outputs were assessed according to general trends over time and vegetation responses (all six biological classes) to extreme hydrological events and relevant and extreme geomorphological change. Results of model testing are presented in chapter 7.

3.3.7 Sensitivity analysis

Analysing uncertainty in the model involved a parameter sensitivity analysis. We used single parameter analyses by comparing the sensitivity index (S) between outputs from different model runs of 62 years. The sensitivity index is calculated from the model output (in this case population density for each of 6 classes) before and after the parameter change, as well as the values of the parameter being tested, before and after its change (Haefner, 1996). Results from the sensitivity analysis are presented in chapter 7, and their use in prioritizing research and monitoring efforts in chapter 8.

3.4 MONITORING PROGRAM

The purpose of developing a monitoring program is to evaluate the achievement of defined management goals. Managers and scientists together set goals detailing predefined limits of change. This has been done in this project and is discussed in detail in chapter 5, but also see Rogers and Bestbier (1997) for a discussion on setting management goals and defining thresholds of change for riverine systems in South Africa, particularly in the KNP. A reciprocal relationship exists between the model and monitoring. The model determines the type of data that needs to be collected and the data help to further test and refine the model according to the defined limits of change. Results from the sensitivity analyses (see Chapter 7) have been used to prioritize subsequent research and monitoring efforts by focussing on the most sensitive variables and parameters. Achievability of setting up a monitoring program needs to be weighed up against limitations of available resources, so some recommendations have been made to prioritise and minimize efforts (see Chapter 8 for details).

3.5 PROTOCOL DEVELOPMENT

The purpose of setting up a protocol was to provide a basis for transferring the expertise gained on the Sabie River to other researchers interested in developing rule based models on different rivers and systems throughout the country. This required a concise, formal documentation, based on literature and our experience, of the sequence of events and processes used to develop a rule based model for the management of riparian vegetation. In addition, the process of model planning, development (especially the use of management goals), testing, use and interpretation were also outlined as these are quite different from those used in more traditional numerical modelling.

Chapter 4

EVALUATION OF THE BLINKS RIPARIAN VEGETATION MODEL

The KNPRRP was established to address the issue of water supply (both quantity and quality) to the natural river environments of the Kruger National Park (Breen *et al.*, 1994) in order to conserve biodiversity in the park. A main aim of the KNPRRP is to predict the consequences of changes to the river, and the responses of organisms to these changes. This is so that the National Parks Board can manage the rivers of the park deterministically to achieve conservation objectives.

The KNPRRP therefore initiated a project in 1996 to draw together the abiotic and biotic information and knowledge collected by the KNPRRP into a suite of qualitative rule based models that would enable researchers and resource managers to predict biotic responses to geomorphological and hydrological changes in the Sabie River (Jewitt et al. 1998). The suite of models (The BLINKS models) included a geomorphological model, a riparian vegetation model, and a fish assemblages model.

In the riparian vegetation BLINKS model, a response of riparian vegetation to geomorphic change is predicted, which in turn is predicted by the geomorphology model on the basis of flow regime and sediment load. The vegetation model makes predictions over time of the change in six identified vegetation types (van Coller *et al.*, 1997) in relation to five functional groupings of geomorphic units (Jewitt *et al.*, 1998). The first research objective of the current project (see section 1.2) was to evaluate the BLINKS riparian vegetation model to ascertain additional knowledge and data needs for improved decision support. The model was evaluated in terms of:

1. Its constraints and assumptions,
2. The use of and potential to incorporate existing data bases,
3. Parsimony of the model structure and its use,
4. Potential to provide decision support for management and to define research to improve decision support, and
5. Its ability to generate auditable output.

4.1 SCRUTINY OF MODEL CONSTRAINTS AND ASSUMPTIONS

Resource, data and time limitations led to some major constraints and assumptions that limited the usefulness and confidence of model output. Some were clearly stated in the model report (Jewitt *et al.*, 1998), but others were identified in this study:

(1) Hydrological influence on the distribution of riparian vegetation was included in an indirect way, through the influence of hydrological disturbance on geomorphology.

- Disturbances by floods and droughts directly and indirectly influence riparian vegetation dynamics and need to be incorporated into the model to increase confidence in output, and to become more relevant to management.

(2) The predicted riparian vegetation state is independent of the previous years riparian vegetation state, i.e. there is no feedback mechanism from the vegetation.

- This is a fundamental biological limitation of the model. A change in vegetation distribution does not occur as an immediate response to a change in geomorphology, but is dependent on antecedent vegetation composition. Consequently the model predicted fluxes in the states of the different vegetation types that were more rapid than can be expected. The influence of antecedent vegetation needs to be explicit in the model.

(3) Riparian vegetation state change is independent of time and occurs as direct and immediate response to geomorphological change. There is direct correlation between riparian vegetation and fluvial geomorphology, and no causal mechanisms operate.

- This severely limits the types and rate of vegetation change that can be predicted. No data on regeneration, growth rates, or longevity of riparian species were used to influence the rate of vegetation change, thus severely limiting the model in its temporal accuracy.
- There was no lag time between the time of geomorphological change and vegetation change, whereas there will always be a period of vegetation establishment on a new geomorphic surface. Understanding the exact nature of the lag time requires data on regeneration, survival and growth rates.

(4) Riparian vegetation response to change in a particular channel type or geomorphological unit is always functionally the same.

- This assumption is based on good, existing correlations between riparian vegetation and fluvial geomorphology. However, it ignores the high degree of variability in the relationship which is a consequence of geomorphological unit spatial placement, flooding characteristics (active, seasonal and ephemeral flooding) and availability of the water table. Geomorphological units should therefore be categorised in terms of associated hydrological processes.

(5) Once geomorphological change has occurred, site availability does not limit riparian vegetation response, and as sites become available, they are occupied by adults of relevant vegetation types. The model does not include smaller-scale causal dynamics.

- The abundance of the existing vegetation needs to be incorporated as a factor limiting site availability due to density dependence. Careful consideration needs to be made of bedrock surface availability along the Sabie River, since bedrock is known to be an important site for the establishment of certain riparian species. The loss of bedrock through an increase in sediment build up will result in bedrock sites becoming limited. In semi-arid regions, water availability also limits the availability of sites for recruitment (particularly establishment) of vegetation. Site availability is an important smaller-scale phenomenon that needs to be incorporated in the future model.

(6) Dispersal and the presence of propagules do not limit the response of riparian vegetation.

- This assumption ignores the fact that species are not uniformly distributed down the length of the river, that their propagules are differentially distributed in time, and that there are limits to their dispersal capabilities and dispersal distance. The river acts as an important dispersal agent for those species close to the active channel, and the distance of dispersal will depend largely on flow characteristics and seed buoyancy. Species far from the channel rely on other dispersal agents or large scale floods. The viability of seeds or propagules of individual species is unknown, but is unlikely to be more than a few months for most riparian species. Propagule availability will depend on the timing of fruiting relative to hydrological events.

(7) Geological change down the length of the Sabie River does not influence riparian vegetation distribution patterns or responses.

- Geological change down the length of the Sabie River is known to influence vegetation patterns. Geology mainly influences the structure and composition of bank vegetation (two vegetation types), and has an indirect influence along the macro-channel floor where it affects the longitudinal gradient and therefore sediment transport. However, this assumption is indirectly addressed via changes in geomorphological structure along the river.

4.2 PARSIMONY OF THE MODEL STRUCTURE AND ITS USE

The use of rule based, pragmatic models promotes inclusion of only relevant information and a structure that reduces ecological complexity without loss of meaningful output. There is nevertheless a fine line between a model that is so simple that its output becomes trivial and one that has too many variables, is complex and unwieldy to manage or use. Parsimony of the BLINKS riparian vegetation model structure and its use was determined by asking the following questions: Are there variables in the model that complicate it unnecessarily, and are there important variables not included that significantly reduce the meaning of the output?

4.2.1 *Variables included in the model*

Variables used in the model were:

- Geomorphological input (five functional groupings of geomorphic units), and

- Riparian vegetation response (six vegetation types).

Using geomorphological functional groups as input proved to be an efficient way of summarising the influence of hydrogeomorphic processes on vegetation, but because the processes were not inherent in the model, it was not possible to determine their direct influence. For example, flooding frequency associated with different geomorphological units is a key factor influencing vegetation pattern (van Coller, 1993), but was not part of the BLINKS geomorphology model output, and therefore not input to the BLINKS vegetation model. Clearly, ensuring that hydrogeomorphic processes are explicit in the BLINKS geomorphology model output, will markedly improve the resolution of predictions.

Parsimony of the model was also enhanced by using functional groups of geomorphological units. Functional groups were based on the degree of bedrock influence, and whether bars were consolidated or unconsolidated. While bedrock influence proved to be an appropriate criterion, grouping as consolidated or unconsolidated resulted in a number of problems in the model. For example, actively flooded lateral bars are unconsolidated while ephemerally flooded lateral bars are consolidated, but in the model all lateral bars are classed as unconsolidated.

Output of the model enhanced parsimony by using six clearly defined vegetation types (van Coller *et al.*, 1997) instead of attempting to model the response of all plant species. Although this reduces the complexity of the model, it introduces the assumption that all species of a particular vegetation type respond to geomorphology in the same way. Good correlation between vegetation types and geomorphology suggests that this was an acceptable approach, but monitoring vegetation types is complex and subsequent management goals (Rogers & Bestbier, 1997) were defined in terms of indicator species and not communities.

4.2.2 Variables excluded from the model

The exclusion of some variables due to time constraints significantly reduces the meaning of the model output. Omission of the hydrological influence of flooding and drought stress was identified above. Although inclusion would increase the complexity of the model, it is an input variable that cannot be ignored.

A minimum requirement for any prediction of vegetation change is a dependancy on the antecedent vegetation state and this was not included in the model. The instantaneous change to another vegetation type within a year predicted by the BLINKS vegetation model, is a biological impossibility. Vegetation processes which lead to change (such as regeneration, survival, mortality and density dependence) are fundamental to predicting vegetation response. It is clear therefore that although complexity of the model is reduced by not having antecedent vegetation as an input variable, confidence in the model output is substantially reduced.

4.3 POTENTIAL TO PROVIDE DECISION SUPPORT FOR MANAGEMENT AND TO DEFINE RESEARCH TO IMPROVE DECISION SUPPORT

Models, or predictive tools, form are an integral component of the iterative decision support system (DSS) outlined for the KNPRRP (Breen *et al.*, 1994; Rogers & Biggs, 1999). Models are used in the DSS to predict the consequences of proposed management actions. It is necessary therefore to evaluate how well the BLINKS riparian vegetation model improves decision making.

The BLINKS riparian vegetation model was developed before the desired state or management goals for the Sabie River had been fully defined, but the main concern of managers was the impact an altered flow regime and increased sediment load on riparian vegetation. Prediction of these impacts became the overall purpose of the BLINKS riparian vegetation model.

The complexity of this task and paucity of data led to some fundamental constraints and assumptions and an inevitable oversimplification. Model predictions were more about presenting the correlation between vegetation and geomorphology than about making realistic process based predictions of change in the vegetation. The ability of the BLINKS riparian vegetation model to provide decision support for management was therefore useful for improving the managers understanding of the correlation between riparian vegetation and fluvial geomorphology, but was limited because output did not serve particular decision making needs, too many fundamental assumptions existed, output was too coarse, and the temporal framework was inadequate. The model could also not be used to adequately define research needs to improve decision support because it lacked critical ecological complexity.

4.4 EXTENT OF KNOWLEDGE BASE USE AND POTENTIAL TO INCORPORATE ADDITIONAL DATA

4.4.1 Vegetation

Definitions of vegetation types and correlations between vegetation types and geomorphological features (van Coller, 1993; van Coller & Rogers, 1995, 1996) were extensively used in the BLINKS riparian vegetation model.

The majority of the existing riparian vegetation data base was not however utilized:

- Probabilities of landscape state changes - a markovian approach (Carter & Rogers, 1995)
- Regeneration and phenology of riparian tree species (Mackenzie, unpublished data)
- Ground water and evapotranspiration (Birkhead *et al.*, 1997)
- Vegetation roughness (Broadhurst *et al.*, 1997)
- Alien species control (KNP staff)
- Phytosociological descriptions along the Sabie River (Bredenkamp & van Rooyen, 1991)
- Population study - *B. salicina* (de Fontein & Rogers, 1995)
- Tree mortality along the Sabie River (van Coller, unpublished)
- Linking hydraulics to vegetation distribution (van Coller, unpublished data)

These data sets provide the potential to deal with many of the short comings of the model identified in sections 4.1 to 4.3:

1. Rates of vegetation type and geomorphological change
2. Riparian vegetation dynamics
3. Water availability and hydrological disturbance

Short comings that can not be addressed by these data sets include:

1. Growth rates of riparian plant species
2. Interactions between plants such as density dependence and competition
3. Riparian vegetation response to non-extreme hydrological events

4.4.2 Geomorphology

Geomorphological data that have been used in the BLINKS riparian vegetation model include:

- Geomorphic unit and channel type definitions and descriptions along the Sabie River (van Niekerk & Heritage, 1993)
- BLINKS geomorphology model (Jewitt *et al.*, 1998), which predicts percentage change in geomorphological units.

Geomorphological data which have not used in the vegetation model include:

- A geomorphological hierarchy of Lowveld rivers (van Niekerk & Heritage, 1993)
- A qualitative sediment movement model for rivers (Nicholson & James, 1995)
- GIS development of representative reaches along the Sabie River (O'Regan, unpublished data; used in Heritage *et al.*, 1997)
- Landscape state changes for a 10 year period on the Sabie River (Rountree, 1997)
- GIS evaluation of channel sedimentation patterns for a bedrock controlled channel in a semi-arid region (van Niekerk & Heritage, 1994).

At present the only input to the vegetation model is the output of the geomorphology model which predicts proportional changes to geomorphic units within a given representative reach, this being based on sediment dynamics. Evaluation of this geomorphological input to the vegetation model showed that:

- Although geomorphological information is available at several scales, the geomorphic unit scale is utilized. There is a need to refine the resolution of the geomorphology model to distinguish between active, seasonal and ephemeral features, and to modify the functional groupings accordingly.
- It would be advantageous to achieve this refinement quantitatively (using flooding frequency probabilities) rather than qualitatively. Rountree's data (1997) could be used to achieve this.
- Definitions of geomorphic states used in the model could be improved using O'Regan's work (unpublished data).

4.4.3 Hydrology

The following data are available:

- Roughness and stage discharge relationships (Broadhurst *et al.*, 1997), which enable the translation of discharge values into local hydraulic conditions.
- Stage discharge relationships at numerous transects along the Sabie and Letaba rivers (Heritage *et al.*, 1997)
- Daily hydrological discharge at 3 weirs along the Sabie River
- ACRU model simulated information (Schulze, 1995)
- Detailed ground water dynamics at one site along the Sabie River (Birkhead *et al.*, 1997)

None of the available hydrological knowledge base was incorporated directly into the BLINKS riparian vegetation model, although the data provide much potential:

- Floods and droughts are important determinants of riparian vegetation distribution patterns.
- Flow frequency data are available for transects and there is a strict relationship between flow frequency and magnitude. This relationship can be used to calculate one from the other in subsequent rules.
- Changes in vegetation distribution as a result of the 1996 flood can be related to flow frequency data (or calculated magnitude) thereby incorporating a direct hydraulic effect into the model.
- The effect of low water level (drought) on tree mortalities can be incorporated as a hydraulic response variable.

Generally, the BLINKS riparian vegetation model is hard coded in Fortran and does not afford the user flexibility to manipulate variables other than geomorphological inputs. A level of flexibility where the user can manipulate variables and parameters important in the model, and even replace values once new or better data become available, is essential.

4.5 ABILITY TO GENERATE AUDITABLE OUTPUT

Output from the BLINKS riparian vegetation model consists of tabulated riparian vegetation states for each of the vegetation types for each year that the model is run. The user can only view the non-graphical outputs and inputs which do not equate to specific management goals. We therefore suggest the following to improve user friendliness and management applicability:

- a user friendly interface, where outputs and inputs are graphically presented,
- direct inclusion and display of management goals, and a warning system to alert managers of goal violation,
- output that can be saved to disk for subsequent analysis,
- output summaries or rule traces that are easy to understand, and assist users to interpret outputs,
- helpful explanatory notes within the model that are visible to the user, and explain the outputs and how they should best be interpreted.

4.6 CONCLUSION AND FUTURE DIRECTION

The riparian vegetation BLINKS model served as a useful exercise in bringing together experts from different disciplines to communicate across their respective disciplines and to build a suite of rule based models with a common management goal in mind. It is clear however, from the evaluation of the constraints and assumptions of the riparian vegetation model, the model parsimony , the extent to which data have been used and can be incorporated, the auditability of the outputs, and its ability to provide useful decision support, that the model goal was too broad to effectively achieve within the time and data constraints.

An alternative approach to developing a more useful model would be to reassess and refine the management goal all together, so that the model has clear explicit and achievable objectives in mind that are geared to a very specific problem. Starfield (1997) emphasises that having clear problem orientated management goals points the way forward to simplifying the ecological complexity in a model to a useful and manageable level. This pragmatic modelling paradigm leads to a shift from a few multipurpose models, to a suite of small single purpose models. We adopted this view to modelling, and present our revised approach in the next chapter where all the problems that have been highlighted in this chapter have been addressed.

Chapter 5

A PRAGMATIC APPROACH TO MODELLING

5.1 CONTEXT FOR PRAGMATIC MODELLING

The pragmatic modelling paradigm that proposes a suite of small single purpose models (*sensu* Starfield, 1997) adopted in this project, requires that management have specific goals clearly stated prior to commencement of model development. It was appropriate, therefore, that whilst evaluation of the BLINKS model was taking place, 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 & Bestbier, 1997; Rogers & Biggs, 1999). The lower level goals are scientifically based, spatially and temporally bounded targets of ecosystem condition. These targets have been termed Threshholds of Probable Concern (TPCs), and 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.

5.2 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 & Biggs, 1999). Research aids in the identification of the main agents of change in river characteristics and the indicators of these agents (Rogers & Biggs, 1999; Figure 5.1). Upper and lower levels of these indicators can be 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 modified if they are found to be invalid or inappropriate.

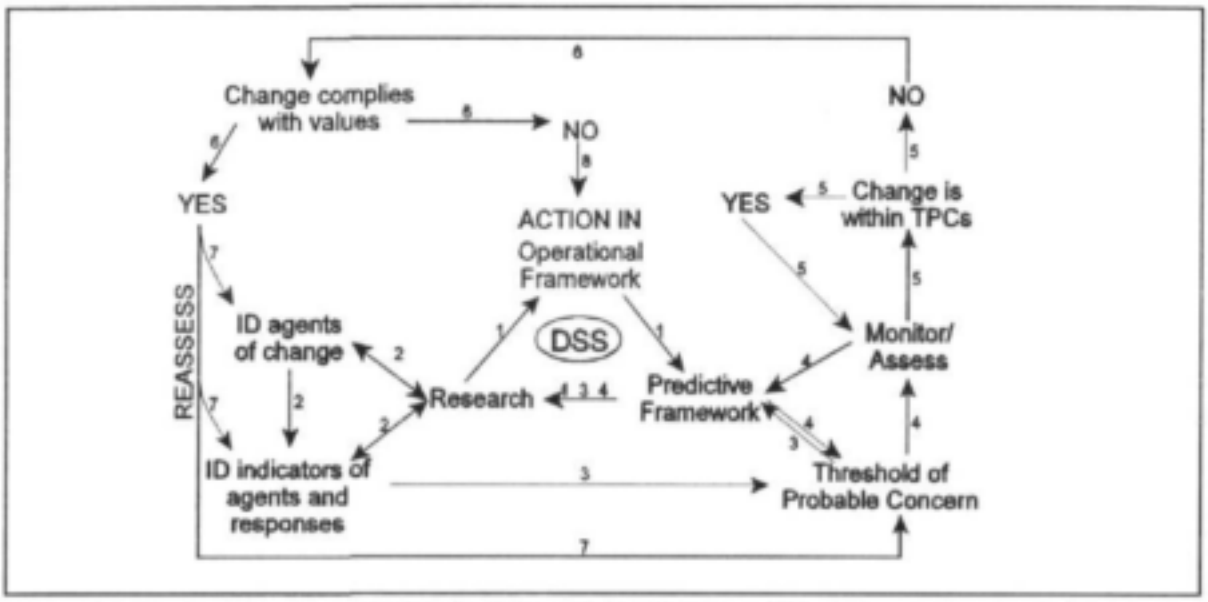

Figure 5.1 The iterative process whereby Research, Prediction and Operations interact with Monitoring of System Response to develop, test and audit Thresholds of Probable Concern (TPCs). The numbers on the arrows define the sequence in which steps are taken. DSS refers to Decision Support System (after Rogers & Biggs 1999).

Monitoring provides a means for evaluating the validity and appropriateness of the TPC, through feeding information regarding change of the indicators back into the predictive framework which ideally is in the form of a model (Rogers & Biggs, 1999; Figure 5.1). 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, then the information is fed to researchers who then use it in their models or experiments to test the validity of the TPCs. 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 that are useful to management.

5.3 THE USE OF TPCs TO GUIDE MODEL DEVELOPMENT

Key to model development is the construction of conceptual models to identify the different components of the model and the relationships between components. A first step, is to construct a conceptual model that embodies all the possible components involved in vegetation dynamics, representing what one would expect to find in reality, and we thus term it the 'entire system model

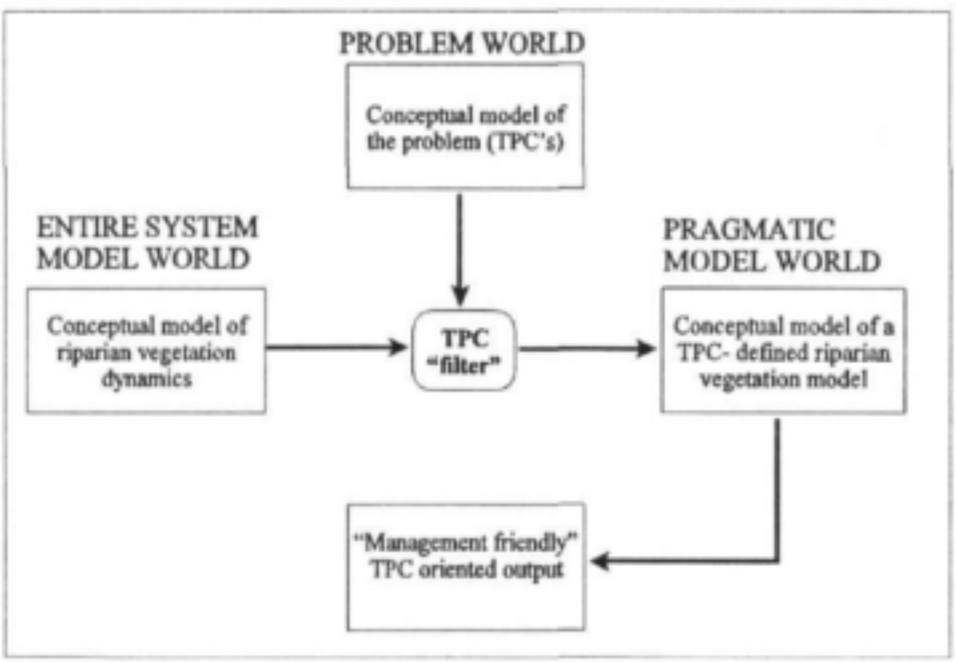

Figure 5.2 The use of the TPCs in guiding model development.

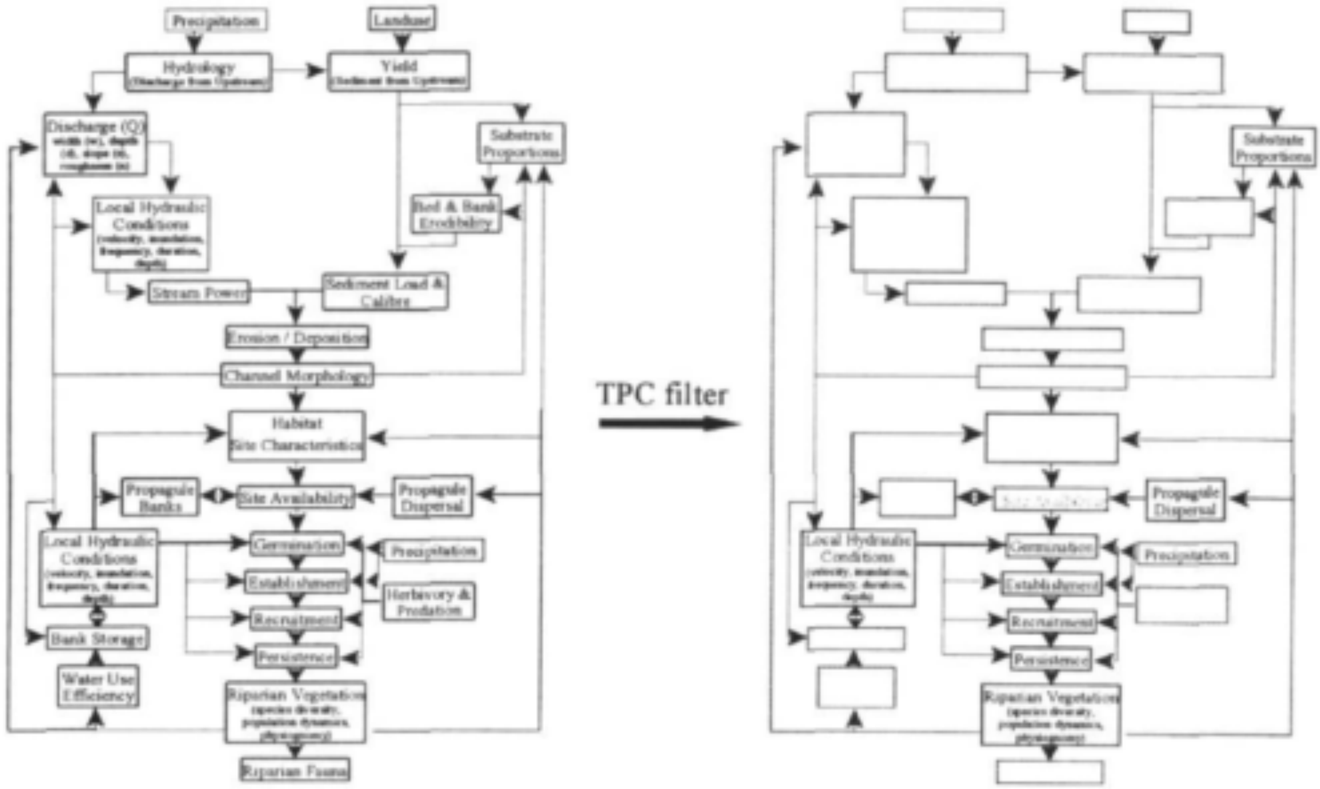

Figure 5.3 An example of the filtering process whereby the unnecessary components of the entire system model world are filtered out by the TPC to form the pragmatic model world that only includes the essential components.

world'. The conventional route to modelling would be to develop a model that includes as many of the components of the real world or 'entire system model world' as possible within the modelling framework. This approach promotes a large multipurpose model that reflects as much of the system dynamics as possible.

In our pragmatic approach, we add a third conceptual model to this process, the 'problem model world' (Figure 5.2). The problem model includes problems that are 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 world to what we have termed the 'pragmatic model world'. TPCs then act to "filter" the academic complexity of the entire system model world. In so doing, only the essential components of the entire system model world that are relevant to management are included in the pragmatic model world. This is best illustrated by the example in Figure 5.3. The entire system model world comprises a detailed conceptualisation 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 world. Management have thus directly guided model development by defining problems (TPCs) which are explicit in the filtering process from the entire system model world to the pragmatic model world. The result is a suite of smaller problem specific models that produce a predictive output useable by managers within their operational framework. The confidence we have in the pragmatic model world is however, also directly related to the context provided theoretically defendable entire system model world.

5.4 THE PROBLEM MODEL 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 & Biggs, 1999). Along the Sabie River these modifications translate into two major areas of potential change that are of concern to managers; a reduced flow regime and increased sediment storage which reduces bedrock influence (Figure 5.4). Managers and scientists

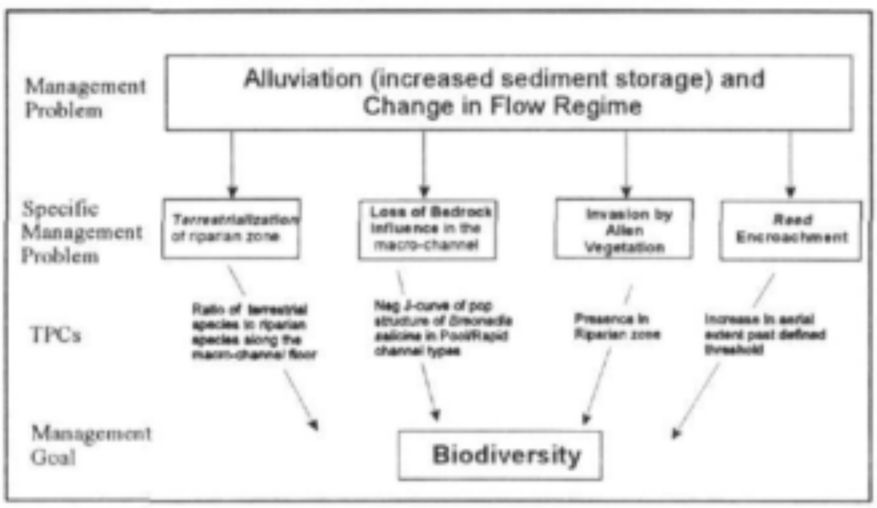

Figure 5.4. The problem model and associated TPCs.

together have identified four key problems associated with increased alluviation and an altered flow regime. These are, terrestrialisation of the riparian zone, loss of bedrock influence in the macro-channel, invasion 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.

5.4.1 TPC for the 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). However, a progressive increase in terrestrial species relative to riparian species within the riparian zone, which we refer to as terrestrialisation, has the potential to result in a decrease in the overall biodiversity of the riparian zone, and is thus a concern to managers. The concern of terrestrialisation applies only to the macro-channel floor (see Figure 1.1) where riparian vegetation is typically dominant. We express the dominance of terrestrial species over riparian species as a ratio of the abundance of established individuals of key terrestrial plant species over the abundance of established individuals of key riparian plant species.

The processes, or agents of change, underlying this phenomenon of an increase in terrestrial species relative to riparian species are, a reduction in flooding frequency for a given stage, reduced water availability from the water table, and increased sediment accumulation on bars. 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 a reduced flooding frequency and an increased distance to the water table. As a result of the ratio being dependent on the position relative to the active channel, it is appropriate that the ratio is always referred to 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 5.5). First the ratio will increase through the loss of riparian vegetation, while terrestrial species abundance remains the same (Figure 5.5 i). This may result from either reduced establishment of riparian individuals through a reduction in flooding frequency, or through the loss of established riparian individuals as a result

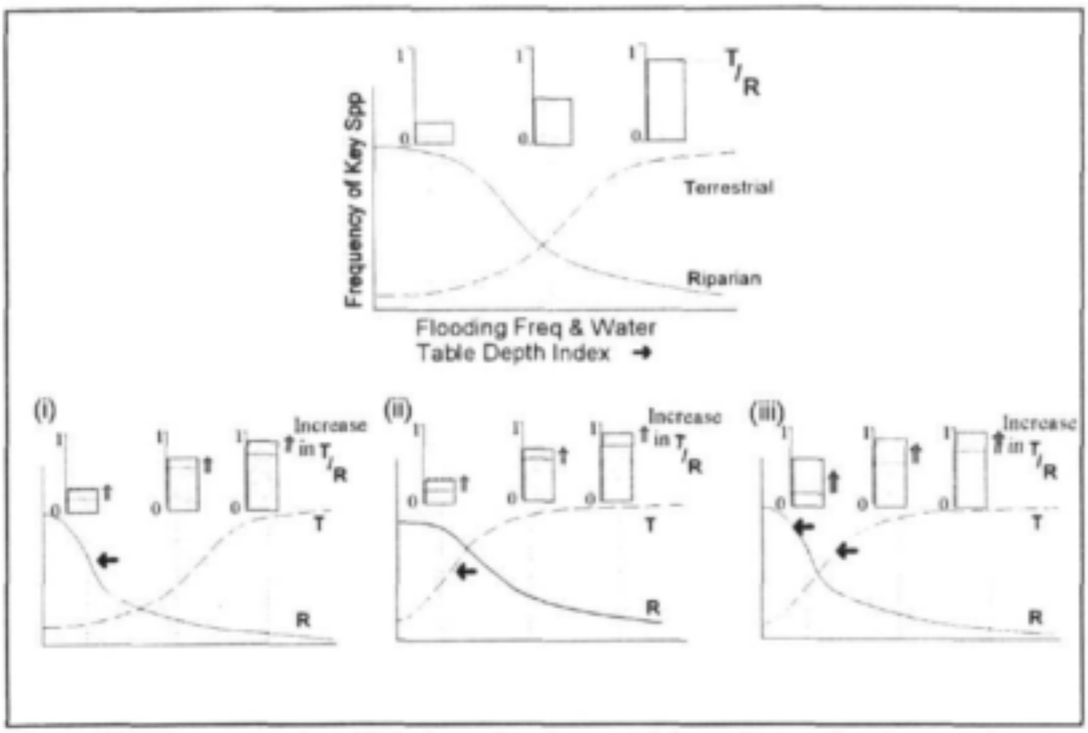

Figure 5.5 Three ways in which the ratio of terrestrial species to riparian species may increase.

of a severe drought. The latter phenomenon was evident during a drought in 1992 where there was large scale mortality of individuals of some riparian species (van Coller & 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.

The second way that the ratio of terrestrial species to riparian species may increase, is through the increase of terrestrial species while riparian species abundance stays the same (Figure 5.5ii). The process resulting in such a change is likely to be a reduction in flooding frequency. Individuals of terrestrial species not tolerant of flooding conditions may establish closer to the active channel as they are no longer disturbed as frequently by flooding during early life stages when they are most vulnerable. Competition for space and light close to the channel where riparian species occur with high cover abundances may act to inhibit terrestrial species from increasing too close to the channel.

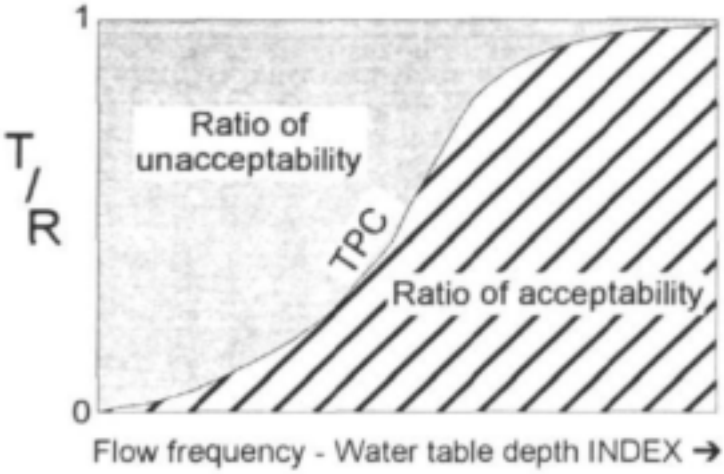

Figure 5.6 A TPC for terrestrialisation represented as a ratio of the abundance of key terrestrial species divided by the abundance of an equal number of key riparian species along an index of flow frequency and water table depth.

The third way that the ratio may increase, is if both riparian species decrease in abundance and terrestrial species increase (Figure 5.5iii). 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. Terrestrial species may also out compete riparian species for space once they have become established resulting in the further reduction of riparian species.

A TPC for terrestrialisation of the macro-channel floor could therefore be the ratio of the abundance of key terrestrial plant species, to the abundance of an equal number of key riparian plant species along an index of flow frequency and availability of water from the water table (Figure 5.6). 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 ratio of acceptability.

5.4.2 TPC for the loss of bedrock influence in the macro-channel

Loss of bedrock influence arises from an increased sediment storage as a result of either increased sediment supply, a reduced ability to transport sediment, or both. A very useful indicator of the loss of bedrock influence is a riparian tree species, *B. salicina*. This species grows close to the river and in close association with bedrock influence (van Coller, 1993). Although *B. salicina* has been shown to germinate abundantly on all substrate types, it is only able to establish on exposed bedrock where sufficient anchorage allows persistence following flooding (MacKenzie unpublished data). Its presence is thus indicative of bedrock influence. The *B. salicina* population will therefore be detrimentally affected by increased sediment storage at the establishment phase of its life cycle and adult populations will progressively decline in abundance.

Another important phenomenon regarding the relationship between *B. salicina* and bedrock is that the population structure of *B. salicina* displays a negative J-shaped curve in channel types with a large proportion of bedrock such as pool-rapid sections (Figure 5.7; De Fontein unpublished data). The negatively skewed J-shaped curve represents a population where abundance is highest in the smallest size classes and decreases as size class increases.

The underlying processes resulting in this population structure are; sufficient suitable bedrock (i.e., includes a suitable flow regime on the bedrock) for establishment of seedlings; continuous, rather than punctuated recruitment; and an increasing rate of mortality within a cohort due to high levels of disturbance (flooding and drought). If bedrock suitable for establishment decreases through increased sediment storage, or through a dramatic reduction in flow frequency, a reduction in recruitment of seedlings would be expected and a loss of a J-shaped population structure (Figure 5.8).

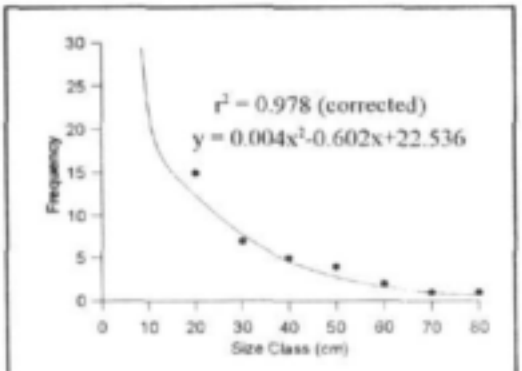

Figure 5.7 Relationship between size class and frequency of individuals of *Breonadia salicina* in pool-rapid channel types (De Fontein unpublished data). Although the curve has been extrapolated for smaller size classes, data on smaller size classes (Mackenzie unpublished data) suggest that it is not an unreasonable extrapolation.

If lack of suitable bedrock occurred over an extended period then there would be a ripple affect into the bigger size classes. This would result in a loss of a J-shaped structure and a decline in density of the larger size classes with eventual extinction of the population in the area. Such characteristics are evident along alluvial dominated braided sections of the Sabie River. Here *B. salicina* has a unimodal or bimodal population structure and lower adult densities (e.g., Figure 5.8c, De Fontein unpublished data, van Coller unpublished data), indicative of previous bedrock influence.

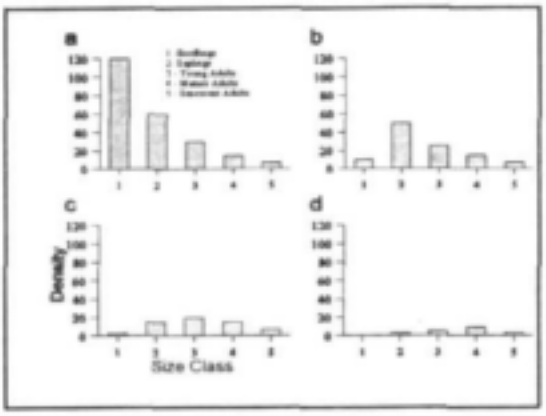

Figure 5.8 An hypothesis of change over time (from a to d) in population size structure of non-germinant individuals of *Breonadia salicina* on a bedrock dominated channel type following a marked increase in sediment storage and a reduced flow frequency after time 'a', leading to a loss of bedrock influence.

Thus, an appropriate TPC for the loss of bedrock influence would be 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 channel types (Figure 5.9). Such a TPC also applies to bedrock anastomosing sections, but the rapid section of pool-rapid channel types was chosen because it is most sensitive to increased sediment storage. Change in these sections is therefore likely to occur before it does in bedrock anastomosing sections (Heritage *et al.*, 1997).

Determining thresholds beyond which the population of *B. salicina* becomes unacceptable involves a critical examination of the attributes of the negative J-shaped curve. A change in the shape of the curve to unimodal, bimodal or positive J-shape would all indicate a reduced establishment of smaller size class individuals, and thus a loss in suitable bedrock establishment sites. A reduction in establishment of smaller size class individuals will also result in a negative J shape with a moderate rather than a steep slope. An overall loss in the population density will result in a shift of the whole curve downwards, and a lowering of the interception point with the y-axis.

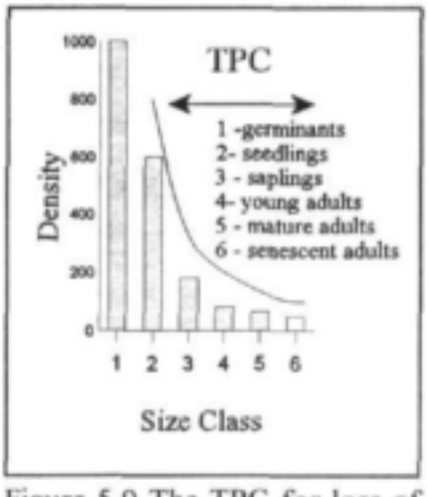

Figure 5.9 The TPC for loss of bedrock influence described by a negative J-shaped population structure for all non-germinant established individuals (size classes 2 to 6) of *Breonadia salicina*.

The shape and the slope of the curve must also be interpreted in the context of large disturbance events. If for instance a large flood occurs, many of the seedlings will be removed and a unimodal curve will result (Figure 5.8 b). If suitable sites for establishment are available in the year following the flood there will be an increase in the seedling size class, returning the population structure to a negative J-shape. Thus, the temporary loss of the negative J-shape curve was not a result of loss of bedrock influence and should not be treated as a concern to managers. The TPC, therefore should always be evaluated in the context of the flow regime where large flood events are accounted for in the interpretation. This highlights the importance of the iterative process to develop, test and audit TPCs (Figure 5.1). If change is not within the TPC, it needs to be assessed whether or not change complies with the values embodied in the vision statement. If it does, then the agents of change (i.e. flooding and alluviation) need to be reevaluated.

5.4.3 TPC for alien vegetation invasion

Invasive alien vegetation poses a threat to the natural diversity of an area through displacement of indigenous plant species and physically altering the environment in which indigenous species grow. Riparian zones are particularly vulnerable to invasion by alien vegetation due to high levels of disturbance and water availability. Patches opened through flooding disturbance are vulnerable to being colonised by alien vegetation. The riparian corridor also acts as an efficient dispersal corridor for alien species through hydrochory and frugivory, further promoting their rapid spread.

The KNP therefore has as a sub-objective for alien vegetation in their management objectives hierarchy, 'to anticipate, prevent entry, eradicate or minimise the influence of non-indigenous organisms so as to maintain integrity of native biodiversity' (Braack 1997). Stemming from this sub-objective is the TPC for alien vegetation in the riparian zone, which is "the rate of alien vegetation control is less than the rate of alien vegetation spread". The TPC would be exceeded *if the spread of alien vegetation, measured as an increase in the frequency and density exceeds the* control of alien vegetation.

5.4.4 TPC for reed encroachment

The reed species *Phragmites mauritianus* was regarded by management to be a problem where it covered large areas of the rivers. This is because reedbeds are believed to utilise large amounts of water (Birkhead *et al.*,1997) and result in the decrease of local biodiversity by out competing other species(van Coller unpublished data).Although there is limited research and understanding of reedbeds, the TPC is: "An increase in aerial extent of reeds beyond a predefined limit" (Braack, 1997).

The development of the reed TPC however, missed out a fundamental step of identifying the agents of change (Figure 5.1). It is not clear what an increase in aerial cover of reeds is an indicator of. What is more likely to be the case is that reeds themselves are important agents of change, rather than indicators of agents of change. The utilisation of water by reeds or the influence on local biodiversity by reeds both imply that reeds are an agent of change rather than an indicator of agents of change. Reeds are also considered to play an important role as physical ecosystem engineers, as they directly or indirectly control the availability of resources to other organisms by causing physical state changes in biotic or abiotic materials (Jones et al. 1997). Reeds alter their environment through increasing flow resistance which promotes increased sediment storage, thus altering the geomorphology and vegetation.

Thus, reeds play an important role as agents of change rather than as indicators of change. We suggest that given the current understanding, the reed TPC is inappropriate, and that alternative TPCs should be sought where indicators of reedbed expansion are used (e.g., species loss, alluvial bar development), rather than the reeds themselves. The reed TPC is not pursued further in this project and should be critically reassessed by KNP management and researchers.

5.5 A PRAGMATIC MODEL WORLD FOR EACH TPC

The filtering process discussed in section 5.3 demonstrates the usefulness of the TPC in formulation of a pragmatic model world which only includes the essential components required to address a specific problem. In this section we present pragmatic model worlds for terrestrialisation of the riparian zone, the loss of bedrock influence, and the encroachment of alien vegetation in the riparian zone respectively, that are a result of the filtering process.

5.5.1 Terrestrialisation of riparian zone

There are two main biotic components to the terrestrialisation pragmatic model world, namely, the life cycle of key riparian species and the life cycle of key terrestrial species (Figure 5.10). The life cycles of each group include the germination on suitable 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 distance from the active channel an individual occurs, whether an individual is riparian or terrestrial, and its life stage.

The interaction of the key riparian and terrestrial species with these five driving forces will result in differential establishment and persistence of individuals of riparian and terrestrial species along a gradient of distance from the channel. Resulting response curves along a gradient of flow

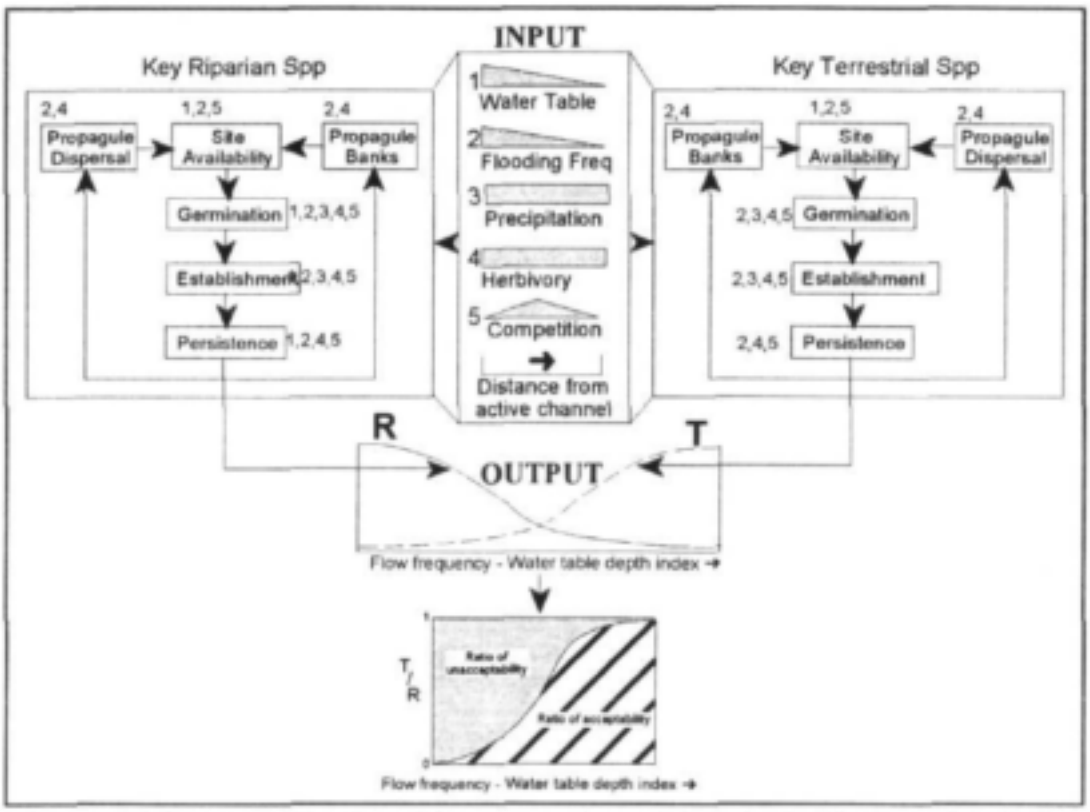

Figure 5.10 Conceptualisation of the pragmatic model world for the terrestrialisation TPC, showing inputs and outputs of the model. The numbers in the key riparian and terrestrial species boxes correspond to the numbers in the input box. T and R are terrestrial and riparian species respectively.

frequency and water availability can therefore be established for key riparian and terrestrial species (Figure 5.10). These two response curves provide the basis for calculating the ratio of the terrestrial species relative to the riparian species, which can be used to audit the TPC (section 5.2).

Some key riparian species for the the Sabie river are *B. salicina*, *Combretum erythrophyllum*, *Nuxia oppositifolia*, *Syzygium guineense*, *Ficus sycomorus* and *Trichelia emetica*, while key terrestrial tree species are *Dichrostachys cinerea*, *Spirostachys africana*, *Lonchocarpus capassa*, *Sclerocarya birrea*, *Ziziphus mucronata* and *Acacia nigrescens*.

5.5.2 Loss of bedrock influence

The TPC for loss of bedrock influence on *B. salicina* is defined by the shape of the population structure. Consequently the model should be concerned with the dynamics of *B. salicina* at the population level. The structure of the population is made up of different functional size classes, namely, germinants, seedlings, saplings and juveniles, young adults, mature adults, and senescing adults (Figure 5.11). Although all size classes are important in the dynamics of the population, the shape of the population structure is determined from the non-germinant size classes. Individuals in each size class have a staying time before moving on to the next size class. A matrix modelling approach was used to deal efficiently with stepping through time.

The shape of the population structure of *B. salicina* depends largely on the probability of surviving in a particular size class or moving on to the next size class. The probability of survival is especially important for germinants and seedlings, since *B. salicina* individuals experience the highest levels of mortality at these young sizes. A number of key interacting factors influence the survivorship of germinants and seedlings; rainfall, flooding characteristics, substrate type, and geomorphic position.

Survivorship of saplings and juveniles, and the adult size classes is not dependent on the substrate type or rainfall since individuals that have reached these size classes have firm anchorage mainly on rock, and have access to the water table. These size classes are influenced more by flow characteristics and the relative geomorphic position of individuals (Figure 5.11).

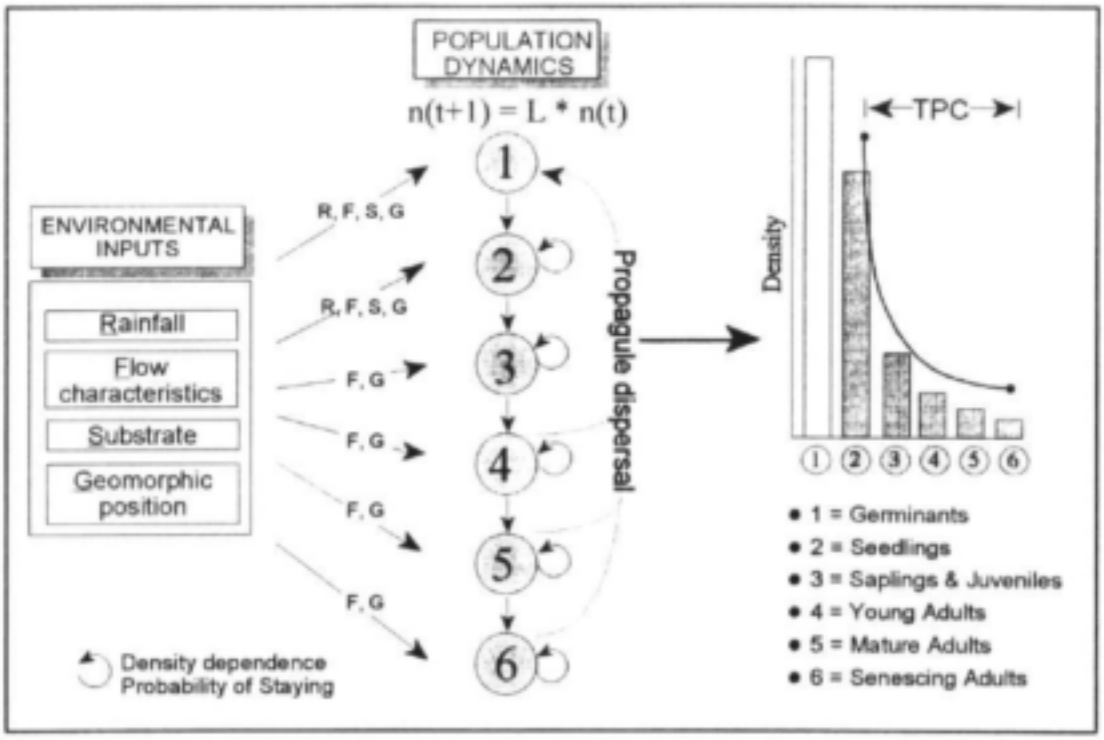

Figure 5.11 Conceptualisation of the *Breonadia* pragmatic model world. The basis of the model is a population matrix model where the population (n) at time t + 1 is equal to the transition matrix multiplied by the population at time t. Density dependence and propagule dispersal are important feedback mechanisms. The output of the model is a population structure of non germinant individuals, from which the TPC may be assessed.

Two important feedback mechanisms exist in regulating the population dynamics of *B. salicina*, namely the influence of density dependence, and the dispersal of propagules. Density dependence is a self regulating phenomenon that occurs for all non germinant individuals. Without density dependence the density of each size class would increase indefinitely which is biologically not possible. It is therefore imperative that density dependence be built into each non germinant size class in order that the population size is self regulating.

The output from the population model provides a population size structure, which forms the basis for checking compliance with the TPC (Figure 5.11, see also section 5.4).

5.5.3 Alien vegetation

The TPC for alien invasive vegetation depends on the rate of alien vegetation control by management being greater than the rate of alien vegetation spread. The pragmatic model world for the alien vegetation TPC (Figure 5.12) is therefore concerned with the pattern and rate of spread of alien vegetation relative to the rate at which it is controlled.

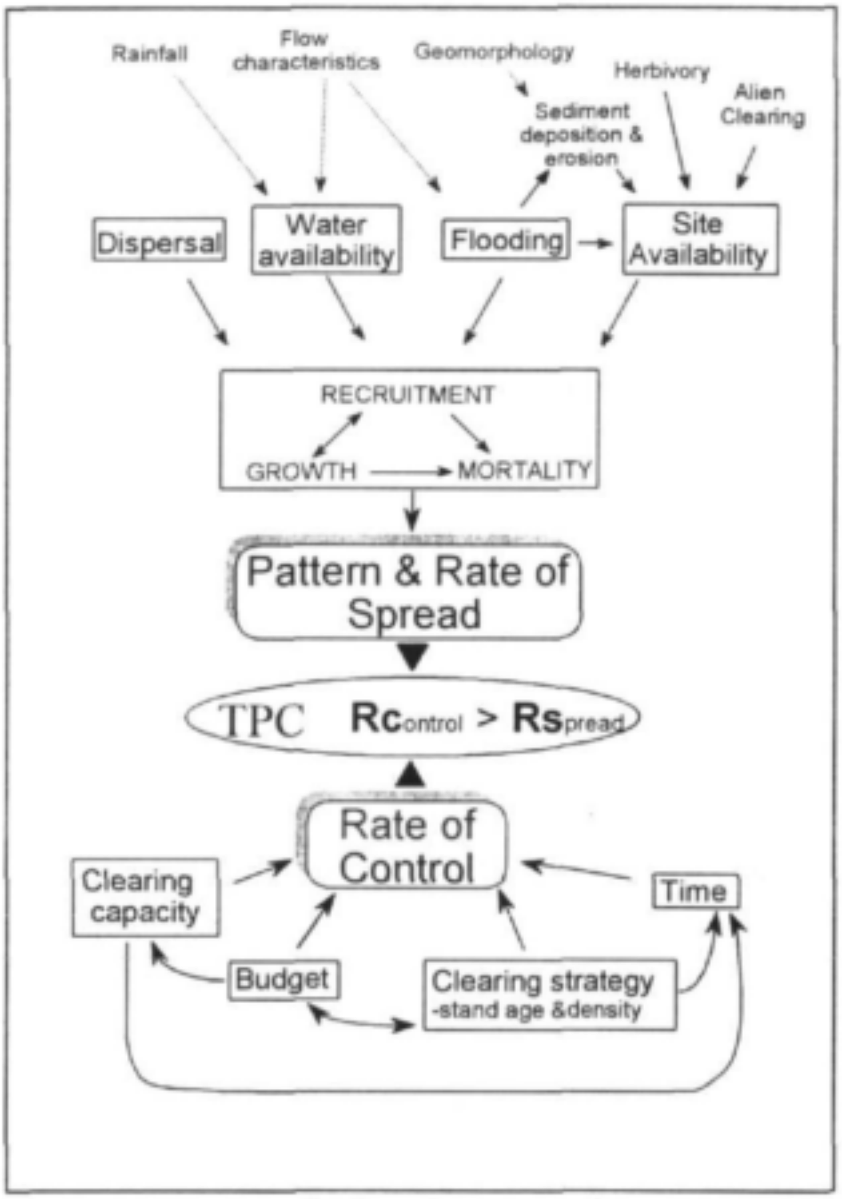

Figure 5.12 Conceptualisation of the pragmatic model world for the alien vegetation TPC.

The spread of alien vegetation in semi-arid riparian zones appears to be driven largely by the disturbance of flooding, an increased water availability, and close proximity of humans. These factors influence recruitment, growth and mortality of an alien species and thus determine the pattern and rate of spread.

The efficiency of alien plant control through clearing operations depends on a number of key interacting factors, namely, the clearing capacity of management, the budget, the time taken to clear stands of alien vegetation, and the clearing strategy used (Figure 5.12). The capacity for clearing alien vegetation will depend largely on the management infrastructure and the budget allocated to the clearing operation. This capacity will influence the time taken to clear the vegetation. Also key to the time taken to clear individuals and stands of alien vegetation, is the strategy used to clear the vegetation. The type (age and the density) of stand that is first cleared plays an important role in determining the cost effectiveness of the operation.

5.6 WHERE TO NEXT ?

The pragmatic approach to model development adopted in this study shifts emphasis from one large system model which caters for all problems and ecological processes to several smaller, problem specific, models which utilize specific subsets of the ecological data base. This, together with the evaluation of the BLINKS model (chapter 4), suggests that any further effort spent on building a rule based model for management of the riparian vegetation should be directed towards the three problem based pragmatic models put forward in this chapter. The scope of the present project, however, anticipated and only budgeted time for the further development of the vegetation BLINKS model.

Within these constraints it was decided that only one of the three models described would be pursued. The loss of bedrock influence was selected as the most appropriate problem, since it had the best available data base, and dealt with the single most fundamental problem facing rivers in the medium to long term. The rest of the report thus focusses on the development of 'the *Breonadia* model', assessment of the model, designing of a monitoring program to audit the TPC, and test and refine the model, and development of a protocol from experience gained.

Chapter 6

STRUCTURE OF THE *BREONADIA* MODEL

The TPC for the loss of bedrock influence in the macro-channel focusses on the population size structure of *B. salicina*. The *Breonadia* model is therefore a population model that focusses on the species life history response to environmental change, and utilizes population projection matrices (Caswell, 1982).

6.1 SIZE STRUCTURED POPULATION MATRICES

The *Breonadia* model uses a size classified life cycle (Figure 6.1). For a population (B) an individual in size class i may survive and grow to size class $i + 1$ with probability Gi or may survive and remain in size class i with probability Si. Reproduction produces new individuals in the smallest size class at a rate Fi.

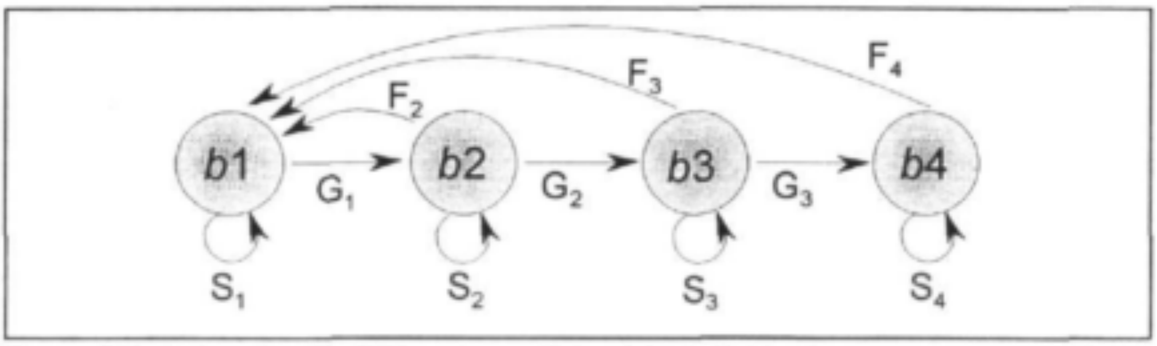

Figure 6.1. A size classified life cycle graph in which individuals can grow no more than a single size class in the interval (t, t+1). From Caswell (1982).

The pictorial description of the life cycle can be translated into a population projection matrix. A projection of the population at time $t + 1$ can be written in matrix form as

$$\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix}(t+1) = \begin{pmatrix} S_1 & F_2 & F_3 & F_4 \\ G_1 & S_2 & 0 & 0 \\ 0 & G_2 & S_3 & 0 \\ 0 & 0 & G_3 & S_4 \end{pmatrix}\begin{pmatrix} b_1 \\ b_2 \\ b_3 \\ b_4 \end{pmatrix}(t)$$

or, more compactly as

$$\mathbf{b}(t+1) = \mathbf{An}\,(t)$$

where $\mathbf{A}$ is the projection matrix and $\mathbf{n}(t)$ is a vector of size class abundances. The matrix is nonnegative, with positive elements only in the first row of *fecundity* (Fi), the diagonal of *staying* in the same size class (Si), and the sub-diagonal of *going* to the next size class up (Gi). This model is widely used for size classified populations, and is referred to as a *standard size-classified model* (Caswell 1989).

The rate of fecundity and probability of staying or going for a given size class i in the standard size classified model matrix can be further modified by survival probability (R_i) and density dependence (Di). The resulting matrix for population B is therefore modified as:

$$\begin{pmatrix} b_i \\ \vdots \\ \\ b_n \end{pmatrix}(t+1) = \begin{pmatrix} S_1.R_1.D_1^{-1} & F_2.D_2^{-1} & \cdots & F_n.D_n^{-1} \\ G_1.R_1.D_1^{-1} & \ddots & & \\ & \ddots & \ddots & \\ & & G_{n-1}.R_{n-1}.D_{n-1}^{-1} & S_n.R_n.D_n^{-1} \end{pmatrix}\begin{pmatrix} b_i \\ \vdots \\ \\ b_n \end{pmatrix}(t)$$

In the *Breonadia* model we use this matrix as the fundamental component to the model structure.

Environmental factors such as rainfall, hydrology and geomorphology input to the matrix to modify the fecundity, probabilities of staying, going, survival, and density dependence. In most cases environmental factors operate as rules that are both quantitative and qualitative. We thus term our model a "rule enhanced, size class population matrix" model.

6.2 GENERAL OVERVIEW OF THE *BREONADIA* MODEL STRUCTURE

The matrix forms the central part of the model functioning. Three environmental variables input to the matrix model: hydrology, geomorphology and rainfall (Figure 6.2). These influence fecundity (defined as the number of germinants produced per individual from each size class) and probabilities of staying, going and survival. Hydrology is in the form of daily discharge (Q) which may be actual flows, scenario flows or flows generated from the ACRU model (Schulze, 1995). These daily flows undergo a frequency analysis to determine the frequency of predefined flow categories or hydrological states. The frequency of the different hydrological states influences the probabilities of staying, going, and survival, and fecundity.

Geomorphology is input to the matrix as proportions of substrate type (seven types) on actively, seasonally and ephemerally flooded features. In the *Breonadia* model these proportions are based either on scenarios of substrate type change or on change in substrate proportions in response to hydrological events (substrate type - hydrological link). Although not part of the present project, output from the geomorphology model. (Jewitt *et al.*, 1998) can also be linked to the *Breonadia* model. The geomorphology model requires a flow and a sediment index which are generated from ACRU simulated information (Schulze, 1995).

Rainfall is in the form of daily rainfall which influences the survival probability of germinants, seedlings and in extreme droughts, adults, as well as the number of germinants produced from each size class (i.e., fecundity).

An important biotic input to the model is size class longevity (Figure 6.2). This is however a problem in the model as there are no growth or size- age data. Known size-age relationships for other tree species have been used to estimate the longevity of each size class. Since assumptions

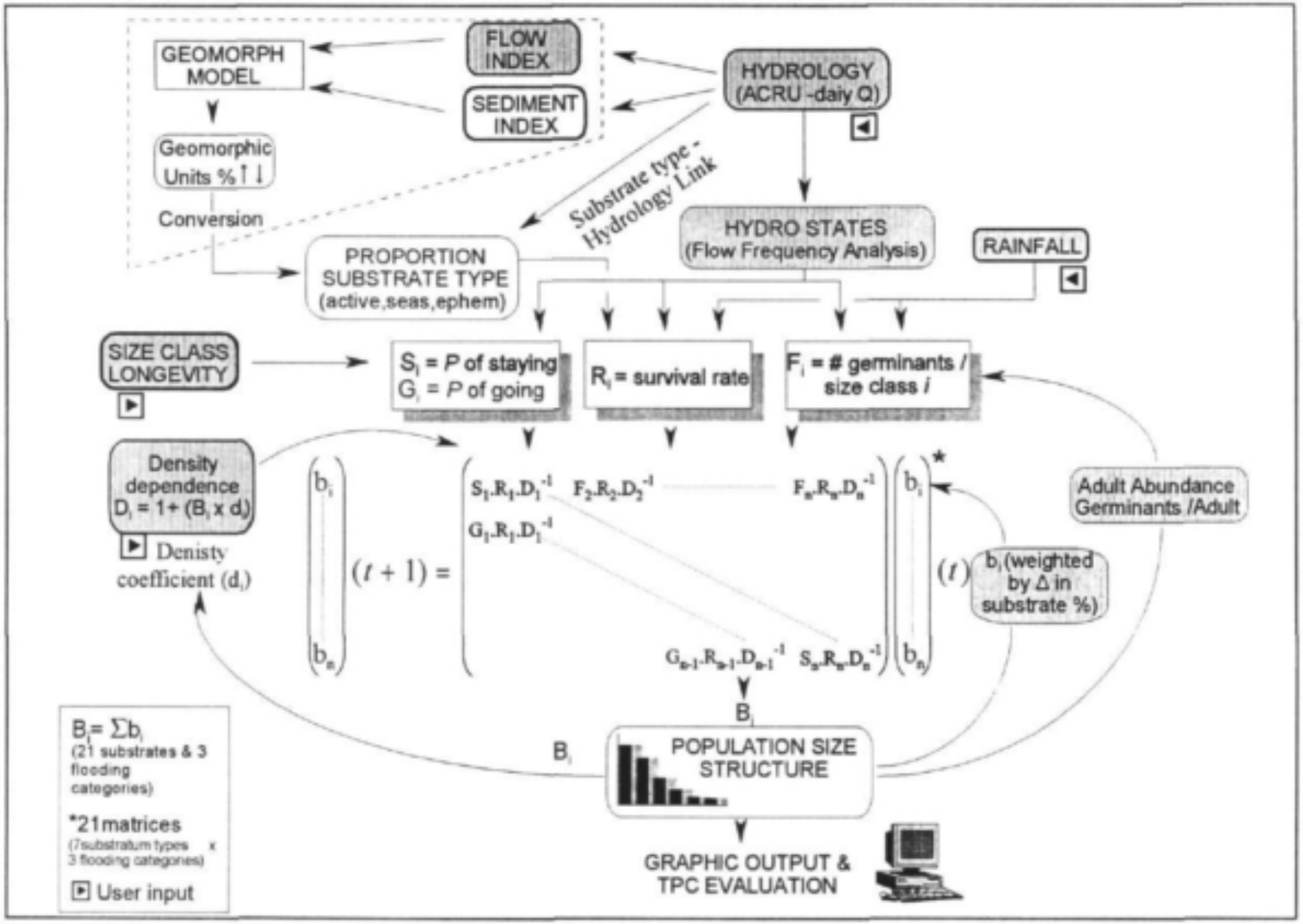

Figure 6.2 Conceptual diagram of the *Breonadia* model structure.

have been made about the longevity of different size classes, the modelled relationship is not absolute, and is open to alteration by the model user once more data become available.

The TPC for loss of bedrock influence in the *Breonadia* model depends on six functional size classes; germinants (not included in the curve for the TPC evaluation), seedlings, saplings and juveniles, young adults, mature adults, and senescent adults. However, to improve prediction of the influence of flooding, these six categories have been divided into fourteen size classes in the matrix structure (i.e., a 14 x 14 matrix). In addition, the model operates as 21 separate matrices to account for the seven substrate types and three flooding categories, one matrix for each category. Following each time step the totals for each size class from the 21 matrices are added to calculate the total density for each size class (i) of the population (B).

There are three important feedback mechanisms in the *Breonadia* model (Figure 6.2):

1. Fecundity, or the number of germinants produced per adult. The density of each of size classes five to fourteen (i.e., adults) from the resultant matrix at time t determines the number of germinants per size class in the projection matrix at time t+1.
2. Density dependence acting on each size class. There is a limit to the number of individuals that can occupy available space. The resultant abundance for each size class is combined with a density coefficient (di) to calculate a density dependence function.
3. The total population at time t feeds back into the vector matrix at time t+1, and is divided on the basis of substrate type proportion.

The resultant output of the matrix model after n time steps is the summation of the 21 matrices, giving the total density of the fourteen size classes (bi). Auditing the TPC requires these fourteen size classes to be grouped into the six functional size classes. The population structure is then assessed for all non-germinant size classes (i.e., five classes: seedlings, saplings and juveniles, young adults, mature adults, and senescent adults) relative to the TPC (see section 5.4.2) and environmental factors that influenced the resultant population.

Each component of the model will be discussed in greater detail, outlining some of the logic, data, rules, assumptions and formats used.

6.3 HYDROLOGICAL INPUT

Hydrology influences individual survival probability, the probability of an individual staying in a size class or going to the next size class, and fecundity of different size classes. Nine hydrological states have been selected to represent functionally meaningful flows for the vegetation (Table 6.1). Daily discharge from either scenario data, ACRU generated data or recorded data undergo a frequency analysis for each year, to determine the frequency of the nine flow categories. The values assigned to these nine categories in the model are not prescriptive and may be changed by the user if necessary.

Table 6.1 Functional hydrological states.

Functional Flow Category	Inundation Frequency	Default Q ($m^3.s^{-1}$) values in the model
1. No Flow	-	0
2. Extreme Low Flows	active	0-1
3. Base Flows	active	1-5
4. Intermediate Flows	seasonal	5-20
5. High Flows	seasonal	20-120
6. Very Small Floods	ephemeral	120-300
7. Small Floods	ephemeral	300-500
8. Large Floods	ephemeral	500-2000
9. Catastrophic Floods	ephemeral	>2000

The model uses these nine states to invoke rules about the occurrence of hydrological events, and at present seven of the states are used: no flow, extreme low flows, base flow, intermediate flows, small floods, large floods, and catastrophic floods. Based on the frequency of different hydrological states, the following rules apply for hydrological events in a given year:

- *If no flows have an annual percentage frequency > 0.8 then a* ***no flow*** *event occurs.*
- *If catastrophic floods have an annual percentage frequency > 0 then a* ***catastrophic flood*** *event occurs.*
- *If large floods have an annual percentage frequency > 0 then a* ***large flood*** *flow event occurs.*
- *If small floods have an annual percentage frequency > 0 then a* ***small flood*** *event occurs.*

- *If the sum of no flows, extreme low flows, and base flows during the wet season (December to May) has an annual percentage frequency > 0.3 and intermediate flows during the wet season has a frequency <0.2, then a* ***drought*** *event occurs.* The rule for droughts is based on observed failed wet seasons in dry years.

The other two hydrological states (high flows and very small floods) do not invoke rules because we do not understand how they might influence *B. salicina*.

A major hydrological assumption in the model is that one event overrides the effects of all other events, therefore events are ranked in order of importance such that "no flow" events override the influence of all other hydrological events; "catastrophic floods" override "large" and "small floods", and "droughts"; "large floods" override "small floods" and "droughts"; and "small floods" override "droughts". This assumption is unrealistic because there will be many instances where two or more events may occur during the year and have compounding influences on the *B. salicina* population. Further refinement of the model will be needed to cater for the complexity of hydrological events.

A number of hydrological scenarios have been included to determine the influence of these different hydrological events on the *B. salicina* population, and are available to the user for selection before running the model. They are:

1. ACRU *simulated information* - Simulated flows generated by the ACRU model (Schulze, 1995) using rainfall data. The flow presently used in the model dates from 1932 to 1993, and is simulated for cell 29 on the Sabie River, located in close proximity to Skukuza.
2. *Catastrophic flows* - Two options are available; an ACRU based data file with a 2500 $m^3.s^{-1}$ flood added during February 1937, or a file where all years have the same mean flow and a 2500 $m^3.s^{-1}$ flood in February 1937. The latter option ensures direct influence of the catastrophic flood without any other confounding hydrological factors.
3. *No Flow event* - An ACRU based file in which flows from February 1953 to November 1953 have been set to zero. This year is a dry rainfall year.
4. *Progressive flow reduction* - ACRU simulated daily flows that are reduced successively each year by 1 % (i.e., after 50 years flow is reduced by 50%) to simulate the influence of

upstream development and the progressive decline of flows in the river.

5. *Drought* - Two options are available; a series of one year droughts or a single two year drought. The one year drought data are ACRU simulated flows, where years 1, 21, 31, 37, 39, 42, 48, 51, 52, 56, and 61 are drought years. Years 10 and 11 have been made drought years in the two year drought option.

6. *Instream Flow Requirements* - Three scenarios are available; (1) maintenance or (2) drought IFR flows at the Skukuza IFR site (Fig. 1.1; Tharme, 1997); (3) flows at the Skukuza IFR site that result from the maintenance IFR flow at the Maritie IFR site (Fig. 1.1; Tharme, 1997), which is closest to Inyaka Dam.

7. *Constant flow release* - Three options are available. (1) Daily ACRU flows are equal to the mean monthly flow, thus reducing the variability in flow. (2) Constant flow releases of either 5.4 (mean monthly flow of the IFR maintenance flow), 10, 20, 30, 40 , or 50 $m^3.s^{-1}$. (3) Daily flows equal ACRU monthly maximum flows. The last option is physically impossible, but is nevertheless biologically interesting.

8. *Random release* -Random release of flows between 0-10, 0-20, 0-30, 0-40, 0-60, 0-80, 0-100, 0-250, 0-500, or 0-1000 $m^3.s^{-1}$. This option assumes that there is a dam upstream able to release these sorts of flows.

9. *User file* - This option allows a hypothetical scenario to be created by the user as input to the model.

6.4 SUBSTRATE TYPE INPUT

Substrate type influences the survival probability of individuals in different size classes. Seven substrate types are utilized: Mud & silt, loose coarse alluvium, loose fine alluvium, firm alluvium, exposed bedrock, gravel and parent soil. Changes in substrate type are either brought about by selection of a scenario of progressive decrease or increase in certain substrate types, or by the selection of substrate change according to hydrological events. In the model, the latter is called a "substrate type - hydrological link". Increase / decrease scenarios are:

1. An annual decrease in the proportion of *rock* by 5 % at time $t+1$ of its original proportion at time t, and an annual increase in the proportion of *loose coarse and loose fine alluvium*

each by 2.5 % at time $t+1$ of the original proportion of rock at time t. The deposition of sediment and resultant loss of bedrock are a primary management concern.

2. An annual decrease in the proportion of *loose coarse and loose fine alluvium* each by 2.5 % at time $t+1$ of their original proportion at time t, and an annual increase in the proportion of *rock* by 5% at time $t+1$ of the original proportion of loose alluvium at time t. If a loss of bedrock is important, it is also necessary to determine a response to increase in bedrock.
3. An annual decrease in the proportion of *rock* by 5 % at time $t+1$ of its original proportion at time t, and an annual increase in the proportion of *firm alluvium* by 5 % at time $t+1$of the original proportion of rock at time t. The same scenario as (1) above, but with a different type of sediment replacing bedrock.
4. An annual decrease in the proportion of *firm alluvium* each by 5 % at time $t+1$ of its original proportion at time t, and an annual increase in the proportion of *loose coarse and loose fine alluvium* each by 2.5 % at time $t+1$ of the original proportion of firm alluvium at time t. Reworking of sediments is not expected to affect *B. salicina*, but needs to be assessed with this scenario.
5. An annual decrease in the proportion of *firm alluvium* each by 5 % at time $t+1$ of its original proportion at time t, and an annual increase in the proportion of *rock* by 5% at time $t+1$ of the original proportion of firm alluvium at time t. The same scenario as (2) above, but with a different type of sediment being replaced by bedrock.
6. No change in substrate proportion. This option allows the influences of hydrology to be detected without the influence of a changing substrate type.

Rules associated with the substrate type hydrology link are not based on any data, but are estimates based on a general understanding of the geomorphology. These rules are open to change by the developer of the model when better data and understanding of the geomorphology are available. Substrate changes linked to hydrological events are governed by rules associated with hydrological events:

1. *If a **catastrophic flood** occurs, then:*

On actively flooded substrates, rock increases by 15 % of its original proportion , and loose *alluvium decreases by 15 % of the original proportion of rock;*

On seasonally flooded substrates, rock increases by 10 % of its original proportion , and loose alluvium decreases by 10 % of the original proportion of rock;

On ephemerally flooded substrates, mudsilt increases by 5 % of its original proportion and parent soil decrease by 5 % of the original proportion of mudsilt.

This rule assumes that catastrophic floods remove sediments on actively and seasonally disturbed features, thus exposing additional bedrock (more so on actively than seasonally disturbed features), while on ephemerally disturbed features, mud and silt is deposited over parent soil.

2. *If a **large flood** occurs, then:*

On actively flooded substrates, rock increases by 10 % of its original proportion , and loose alluvium decreases by 10 % of the original proportion of rock;

On seasonally flooded substrates, rock increases by 5 % of its original proportion, and loose alluvium decreases by 5 % of the original proportion of rock;

On ephemerally flooded substrates, mudsilt increases by 2.5 % of its original proportion, and parent soil decrease by 2.5 % of the original proportion of mudsilt.

This rule assumes the same as catastrophic floods, but exerts less of a change.

3. *If a **small flood** occurs, then:*

On actively flooded substrates, rock increases by 2.5 % of its original proportion , and loose alluvium decreases by 2.5 % of the original proportion of rock;

On seasonally flooded substrates, loose alluvium decreases by 1 % of its original proportion , and rock increases by 1 % of the original proportion of rock.

This rule assumes the same as large floods, but causes less change and does not influence ephemerally disturbed features.

4. *If a **drought** occurs, then:*

On actively flooded substrates rock decreases by 5 % of its original proportion, and loose alluvium increases by 5% of the original proportion of rock.

This rule assumes that sedimentation will occur in the absence of high flows due to reduced sediment transport capacity.

6.5 RAINFALL INPUT

Rainfall influences fecundity and the survival probability of different size classes. Rainfall is in the form of average daily rainfall and originates from ACRU (Schulze, 1995). In the model rainfall is converted into rainfall-states that are biologically meaningful to *B. salicina*. Total annual rainfall is important to both the number of germinants produced by an individual (fecundity) and the survival of individuals in larger size classes. It is therefore necessary to distinguish between wet, dry, and intermediate rainfall years. Rules are based on data taken from known dry and wet years. The rules for rainfall events are:

1. *If total rainfall during the wet season (December to May) is < 300 mm then it is a* ***'dry rainfall year'****, if 300-550 mm then an* ***'intermediate rainfall year'****, and if > 550 mm then it is a* ***'wet rainfall year'***.

Periodicity of rainfall within the year is also an important determinant of the survival of germinants and seedlings. Again, rules are based on data from known wet and dry years. Rules for wet and dry periods in a rainfall year, are:

Germinants:

1. *If there is no rain for 20 or more days, two or more times in the wet season (December to May), or three or more times in the dry season (June to November), then* ***'dry period events'*** *have occurred for the rainfall year,* or
2. *If it rains for seven or more consecutive days three or more times in the wet or dry season, then* ***'wet period events'*** *have occurred for the rainfall year,*

Seedlings:

- *If there is no rain for 20 or more days, and this occurs three or more times in the wet season, or three or more times in the dry season, then* ***'dry period events'*** *have occurred for the rainfall year,* or

- *If it rains for seven or more consecutive days, two or more times in the wet or dry season, then* ***'wet period events'*** *have occurred for the rainfall year.*

6.6 SIZE CLASS LONGEVITY

The relationship between size and age is a key factor for determining how long an individual will remain in each size class before moving to the next size class. The relationship (Figure 6.3) for germinants, seedlings and saplings was based on measured data (Mackenzie unpublished). Young, mature and senescent adult size-age relationships had to be estimated because data for the larger size classes are scarce. The influence of flooding was found to be closely related to size. The six functional size classes were therefore further divided into fourteen to allow the influence of flooding to act at a finer size scale.

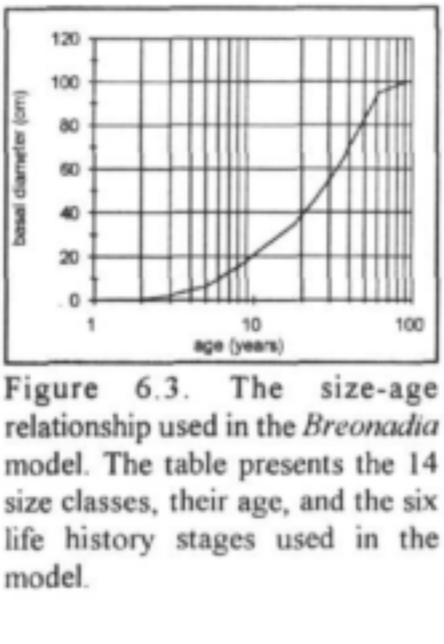

Figure 6.3. The size-age relationship used in the *Breonadia* model. The table presents the 14 size classes, their age, and the six life history stages used in the model.

Size Class	Size: Basal Diam (cm)	Age (Years)	Life History Stage
1	0-0.025	1	germinant
2	0.025-1	2	seedling
3	1-3	3	seedling
4	3-10	5	sapling/juvenile
5	10-20	8	young adult
6	20-30	12	mature adult
7	30-40	18	mature adult
8	40-50	24	mature adult
9	50-60	30	mature adult
10	60-70	37	mature adult
11	70-80	44	senescent adult
12	80-90	52	senescent adult
13	90-100	62	senescent adult
14	>100	92	senescent adult

It was important that the estimates made for the latter three functional size classes were based on trees that were as similar to *B. salicina* as possible. The only existing measured data for trees that are both African and riparian was for a few riparian *Acacia* species (*Acacia robusta*, *Fadherbia albida* and *Acacia xanthophloea*; Gourlay, 1995). Since there is considerable uncertainty surrounding the size-age relationship for *B. salicina*, it has not been hard coded in the model, and may be altered by the user when more accurate information regarding size-age relationships become available.

6.7 FECUNDITY

Fecundity is expressed as the number of germinants originating per individual from each adult size class and values are based on actual measured field data (Mackenzie unpublished). Fecundity is influenced by biotic factors such as the density of the size class, and density dependence which influences fertility, and by two environmental inputs, hydrology and rainfall (Figure 6.2).

Fecundity is not the same for different size classes. The first four size classes (i.e., 0 to 10cm basal diameter) do not produce germinants. Fecundity is weighted for size classes five to fourteen since young and senescent adults produce fewer germinants than mature adults. Rules applied for fecundity relating to size class are:

1. *Young adults (size class five), are down weighted by a factor of 0.4 and mature adults in size classes six and seven, by 0.6 and 0.8 respectively. Mature adults in size classes eight to ten are not weighted. Senescent adults in size classes eleven, twelve, thirteen and fourteen, are down weighted by factors of 0.8, 0.7, 0.6 and 0.5 respectively.*

Fecundity differs according to adult density. Sparsely distributed adults produce fewer germinants than densely distributed adults because of less seed input. Density of adults has been classed as high (>10 individuals. ha^{-1}), medium (2 to 10 individuals. ha^{-1}) or low (<2 individuals. ha^{-1}). The following rule is applied:

2. *If **adult density** is high, medium or low, then, fecundity per size class is either normal, ½ of normal, or $^{1}/_{6}$ of normal respectively. Normal refers to the default fecundity for active, seasonal and ephemeral features when no hydrological events or large floods occur, or the calculated fecundity when other hydrological events occur.*

The nature of the hydrological event determines fecundity based on data measured during a "no event" and a "large flood" in 1996 (Mackenzie unpublished). With this limited knowledge, estimates are made for those events where no data are available. The rules are:

3. *If a **hydrological event** occurs, then the values under optimal conditions (no event) are weighted according to the type of event (no flow event, catastrophic, large or small flood, or a drought) and the inundation frequency (active, seasonal, and ephemeral) of the substrate type (Table 6.2).*

Table 6.2 Weighting factors for the influence of hydrological events on fecundity. x = the observed number of germinants per adult under no event conditions (Mackenzie unpublished).

Flow Freq of Substrate Type	No Event **(observed)**	Catastrophic Flood (estimated)	Large Flood **(observed)**	Small Flood (estimated)	No Flow (estimated)	Drought (estimated)
active	x	$0x$	$0.005x$	$0.006x$	$0.005x$	$0.50x$
seasonal	x	$0x$	$0.007x$	$25x$	$0x$	$0.25x$
ephemeral	x	$0x$	$20\,000x$	$1x$	$0x$	$0x$

Although at present the model uses these values (Table 6.2), the weighting factors may be changed by the user. The rules for weighting the fecundity according to size class, adult density, and hydrological events occur simultaneously. Resulting fecundity is then further modified by rainfall which either increases or decreases fecundity depending on whether a wet or a dry year occurs. The rainfall rule for fecundity is:

4. *If total annual rainfall results in a **'dry rainfall year'** (see section 6.5) then fecundity is down weighted by a factor of 0.5, if it is an **'intermediate rainfall year'** then fecundity remains unchanged, and if it is a **'wet rainfall year'** then fecundity is up weighted by a factor of 1.5.*

A major assumption in these rules is that fecundity is independent of the substrate type and this needs to be addressed in further research.

6.8 SURVIVAL PROBABILITY

The probability of survival of an individual from one year to the next depends firstly on whether or not an event (i.e., flooding, drought, or rainfall) has occurred. If there is no event then default survival probabilities are assigned to different size classes for each of three inundation frequencies and seven substrate types. Probabilities are based on data measured in the field (Mackenzie unpublished data, van Coller unpublished) as well as estimates for those size classes, inundation frequencies and substrate types where no data were available. Since there is uncertainty about many of these probabilities, they are not hard coded in the model, but may be changed by the user when better estimates become available.

6.8.1 Hydrological Events

Hydrological events alter the probability of survival through the removal of individuals during flooding, the increase of micro-site availability for establishment following flooding, or mortality during a drought. The model at present, deals with the influence of a no flow event, catastrophic, large and small floods, and drought on survival probabilities.

Our understanding of the influence of flooding in the model has been based on data collected before and after the 1996 flood (Mackenzie unpublished data, van Coller unpublished). A relationship between the probability of being removed by the flood ($P_{removal}$) and the fourteen size classes (Figure 6.4) showed that $P_{removal}$ decreased with an increase in size class. The 1996 flood corresponded to a "large flood" hydrological state. There is little understanding of the influence of small and catastrophic floods. We therefore use the same relationship for large floods, for these two events, but have either decreased $P_{removal}$ for small floods (by a factor of 0.25, called the "small flood factor") or increased for catastrophic floods (by a factor of 4, called the "catastrophic flood factor"). Once again these factors have not been hard coded into the model and can be altered by the user.

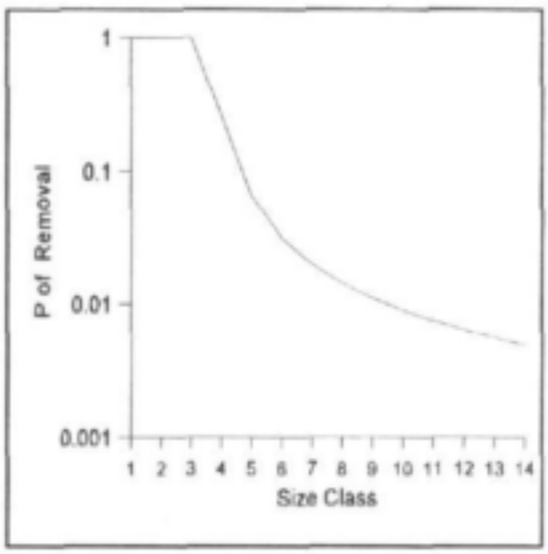

Figure 6.4. Probability of being removed by a large flood for different size classes. The function applied to size classes 3 to 14 is $y = 1.654\,x^{-1.252}$, corrected $r^2 = 0.91$.

Rules used for the influence of drought events on survival probability are based on records of *B. salicina* mortality during the 1992 drought (van Coller and Rogers 1995). Rules used for the influence of "no flow" on survival probabilities have been estimated, as there are no records of the Sabie River not flowing for most of the year.

Rules associated with the influence of hydrological events differ for three categories; germinants (size class 1), seedlings (size classes 2 and 3), and saplings to senescent adults (size classes 4 to 14) and according to whether individuals are growing on actively, seasonally or ephemerally flooded features.

6.8.1.1 Germinants

On actively and seasonally flooded substrates, hydrological events will decrease the survival probability of germinants, while on ephemerally flooded substrates, a small or large flood will increase the chance of survival. Intensities of flooding on ephemeral substrates are less severe during a small or large flood, and thus do not remove individuals, but instead increase water and micro-site availability. Catastrophic floods, however, have the same influence on individuals on ephemerally flooded substrates as they do on active and seasonal substrates. Survival probability following a drought is unaffected on actively flooded substrates, is reduced on seasonally flooded substrates, and is zero on ephemerally flooded substrates.

Breonadia salicina disperses seed from April to July, and by December the seed has lost its viability (Mackenzie unpublished). The timing of flooding events therefore determines survival probability of germinants. The rules are:

1. *If a **no flow** event occurs, then probability of survival (R) = 0, for actively, seasonally, and ephemerally flooded substrates.*

2. *If a **catastrophic flood** occurs, then R = 0, for actively, seasonally or ephemerally flooded substrates.*

3. *If a **large** or **small flood** occurs, then for;*

   (a)Actively and seasonally flooded substrates, from, January to March, $R = R_{no\ event}$ *or from April to December,* $R = R_{no\ event}$ * *(1- the* $P_{removal}$ *by a large or a small flood) * 0.1, 0.08, 0.06,0.04, or 0.02 for April, May, June, July,*

or August to December respectively. (It is evident that if a large flood occurs from April to December, $R = 0$, as the $P_{removal} = 1$, see Figure 6.4).

*(b)Ephemerally flooded substrates, from, January to March, $R = R_{no event}$, or from April to December, $R = R_{no event}$ * (1- $P_{removal}$ by a large or small flood) * 1.6,1.4,1.2,1.0, or 1.0 for April, May, June, July, or August to December respectively.*

4. *If a **drought** occurs, then for,*

   (a) actively flooded substrates, $R = R_{no event}$

   *(b) seasonally flooded substrates, $R = R_{no event}$ * (1- event weight),*

   (c) ephemerally flooded substrates, $R = 0$.

6.8.1.2 Seedlings

Timing of hydrological events is not as critical for seedlings as for germinants because unlike germinants, seedlings are present throughout the year. However, after a flood, individuals that remain (1- $P_{removal}$; Figure 6.4) have a certain probability of survival that is dependent on substrate type. This is because certain substrate types, such as rock and firm alluvium provide better micro-site conditions for survival after the flood than types such as coarse and fine alluvium. These probabilities are based on data collected after the 1996 flood (Mackenzie unpublished).

The rate of seedling increase after a flood has also been included. Field studies after the 1996 floods revealed that germinants grew into seedlings within the first year after a flood event (Mackenzie, unpublished; Table 6.3).

The rules therefore are:

1. *If a **no flow** event occurs then for 1st and 2nd year seedlings, on actively, seasonally, and ephemerally flooded substrates, $R = 0$.*
2. *If a **catastrophic, large or small flood** occurs, then on actively, seasonally and ephemerally flooded substrates;*

   R= R (following the event on actively, seasonally and ephemerally flooded *substrates) * ((1-$P_{removal}$) + rate of increase on actively, seasonally and ephemerally flooded substrates following the flood (Table 6.3)); for 1^{st} year seedlings*

*R = R (following the small flood on actively, seasonally and ephemerally flooded substrates) * (1-$P_{removal}$) for 2^{nd} year seedlings.*

3. *If a **drought** occurs, then for 1^{st} and 2^{nd} year seedlings on,*

   (a) actively flooded substrates; $R = R_{no\ event}$,

   (b) seasonally flooded substrates; $R = R_{no\ event} * 0.8$,

   (c) ephemerally flooded substrates; $R = R_{no\ event} * 0.6$.

Table 6.3. The factor of increase of 1^{st} year seedlings following a small, large or catastrophic flood on actively (actv), seasonally (seas) and ephemerally (ephm) flooded substrates.

Substrate Type	Small Flood			Large Flood			Catastrophic Flood		
	actv	seas	ephm	actv	seas	ephm	actv	seas	ephm
Mud/Silt	1	1	1	1	1	1	1	1	1
Rock	1.2	2	1	1.8	8.2	1	1.8	8.2	2
Loose Coarse Alluvium	1	1	1	1	1	1	1	1	1
Loose Fine Alluvium	1	1	1	1	1	1	1	1	1
Firm Alluvium	15	1	1	30.4	1	1	30.4	1	1
Gravel	1	1	1	1	1	1	1	1	1
Soil	1	1	1	1	1	1	1	1	1

6.8.1.3 Saplings to Senescent Adults

The survival probabilities for the remaining size classes influenced by flooding are affected only by the probability of removal (Figure 6.4). The rules are:

1. *If a **no flow** event occurs, then on,*

   (a) actively flooded substrates; $R = R_{no\ event} * 0.5$,

   (b) seasonally flooded substrates; $R = R_{no\ event} * 0.3$,

   (c) ephemerally flooded substrates; $R = R_{no\ event} * 0.1$.

2. *If a **catastrophic**, **large** or **small flood** occurs, then on actively, seasonally and ephemerally flooded substrates, $R = R_{no\ even} * (1 - P_{removed}$ by a small, large or catastrophic flood).*

3. *If a **drought** occurs, then for,*

   (a) actively flooded substrates, $R = R_{no\ event}$,

   (b) seasonally flooded substrates, $R = R_{no\ event} * 0.8$,

   (c) ephemerally flooded substrates, $R = R_{no\ event} * 0.6$.

6.8.2 Rainfall

Rainfall at a site affects the substrate moisture conditions, and thus plays a role in survival probabilities of individuals. Survival of germinants and seedlings may be positively or negatively influenced by rainfall depending on whether wet or dry periods occur within the given rainfall year (see section 6.5), while the survival of saplings to senescent adults is only negatively influenced by dry rainfall years. The rules are:

1. *If **'dry period events'** occur (see section 6.5) during the wet or dry season of the rainfall year, then,*

   for germinants (size class 1), survival probability decreases by 50%,

   for seedlings (size class 2 and 3), survival probability decreases by 25 %.

2. *If **'wet period events'** occur during the wet or dry season of the rainfall year, then,*

   for germinants (size class 1), survival probability increases by 25%,

   for seedlings (size class 2 and 3), survival probability increases by 25 %.

3. *If the year is a **'dry rainfall year'** then the probability of survival decrease by 10 % for all size classes from saplings to senescent adults.*

These rules for rainfall events are only applied in the model after the rules for hydrological events have been applied. Thus, the resulting survival probabilities from hydrological events are further modified by any rainfall events.

6.9 PROBABILITY OF STAYING AND GOING

The probability of 'staying' in a particular size class or 'going' to the next size class depends on the size class longevity (Figure 6.3) and for certain size classes, hydrological events. Flooding and "no flow" events will both influence the staying time in a size class by altering the growth rates of individuals. The probability of staying in a size class (S) is based on field observations where individuals on bedrock sites, highly disturbed by flooding, never increase in size as their stems are continually broken or damaged by floods, thus increasing their staying time in a size class. The probability of an individual being damaged by the flood in 1996 had a unimodal relationship with size (van Coller unpublished). Individuals in size class eight were most susceptible to damage (Figure 6.5) and the smaller size class individuals were removed by the flood rather than damaged (Figures 6.4 & 6.5). The relationship between probability of damage and a large flood was used to estimate the probability of damage by a small or catastrophic flood. It is down weighted for small floods (by a factor of 0.25, called the "small flood factor") and increased for catastrophic floods (by a factor of 4, called the "catastrophic flood factor").

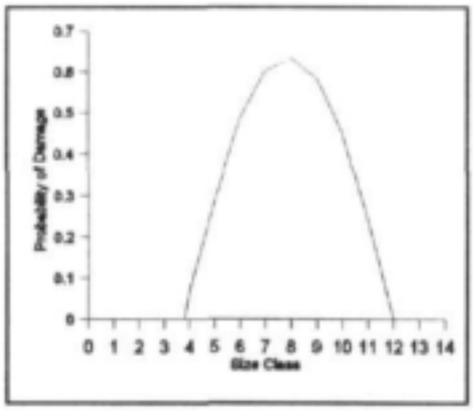

Figure 6.5. The probability of damage to *Breonadia salicina* by a large flood in relation to size (size class). The curve fitted to data has the function $y = -0.00041x^2 + 0.036x - 0.147$, corrected $r^2 = 0.72$.

No flow events also reduce growth rates and thus increase staying time to 1 for all size classes due to reduced water availability.

The rules are:

1. *If **no hydrological event** occurs, then;*

$$S = \frac{(size\ class\ longevity(SCL) - 1)}{SCL}$$

2. *If a **no flow** event occurs, then;*

$$S = 1.$$

3. *If a **large flood** occurs, then;*

$$S = \left(\frac{(SCL-1)}{SCL} * \ Pdamage\ by\ a\ large\ flood\ (i.e.,\ Figure\ 6.5)\right) + \frac{(SCL-1)}{SCL}$$

4. *If a **small flood** occurs, then;*

$$S = \left(\frac{(SCL-1)}{SCL} \ * \ Pdamage(large\ flood) \ * \ small\ flood\ factor(0.25)\right) + \frac{(SCL-1)}{SCL}$$

5. *If a **catastrophic flood** occurs, then;*

$$S = \left(\frac{(SCL-1)}{SCL} \ * \ Pdamage(large\ flood) \ * \ catastrophic\ flood\ factor(4)\right) + \frac{(SCL-1)}{SCL}$$

Droughts may increase the probability of staying by increasing water stress and reducing growth rate, while wet years may decrease the probability of staying by increasing the growth rates. These two environmental factors have not been incorporated into the *Breonadia* model, but should be considered in further refinement.

By using size class longevity to determine staying time, the assumption that individuals have equal growth rates on different substrate types is made. This is not probable and should be considered in further developments of the model.

The probability of going to the next size class is calculated from the probability of staying as: (1-the probability of staying). Future developments of the model should consider the possibility of jumping size classes, if for instance growth conditions are highly favourable.

6.10 DENSITY DEPENDENCE

Populations are constrained by resource limitations and are thus density dependent. Density dependance is included in the model by calculating the matrix elements (a_{ij}; the diagonals of staying and going, and the top line of fecundity; see section 6.1) as functions of density. We apply the density function:

$$a_{ij} = \frac{a_{ij}(0)}{1 + (d_i . b_i)}$$

where b is the resultant density for size class i, and d is the density coefficient of size class i (Caswell, 1989). Thus, the strength of density dependence is determined by the density coefficient and population size. Little is known about density dependence in *B. salicina* and default values for d can thus be changed by the user for each of the fourteen size classes in terms of survival and fertility.

A major assumption is that density dependence operates within given size classes and is the same on all substrate types, although different substrate types support different densities of *B. salicina* (Mackenzie unpublished, van Coller unpublished). Further research into density dependence would enhance further refinements of the model.

6.11 VECTOR MATRIX

The vector matrix is the resultant population at time t that is applied to the projection matrix at time t+1. There are 21 projection and vector matrices (three inundation frequency categories * seven substrate types) that operate, and after each time step all vector matrices are added together to calculate the total population for each size class on all substrates and inundation frequency categories. These totals are then divided between 21 matrices at the next time step to become vector matrices.

This division to form 21 vector matrices at time t+1, incorporates substrate type proportions, and makes the assumption that each substrate type supports equal densities of *B. salicina*. This assumption provides the potential for future refinement of the model.

6.12 USER INTERFACE, MODEL INPUTS AND MODEL OUTPUTS

The *Breonadia* model was coded in Visual Basic (Microsoft version 6.0), which provides a user-friendly and graphically pleasing interface. It also maintains a level of flexibility for the user because it is an event driven program, as opposed to a procedural program, which gives the user control over which rules and procedures to invoke. It takes full advantage of the Windows environment by utilising multiple Window platforms. An additional advantage of programming in Visual Basic is that the model can be made self executable and only requires Windows to operate, thus facilitating its transfer to managers. The Windows environment also allows for various help facilities to be included to aid and guide the user in how to operate the model and interpret its outputs. Four essential components of the model interface are:

1. Adjustable default parameters
2. Model inputs
3. Model outputs
4. Explanatory notes and HELP facilities

6.12.1 Adjustable Default Parameters

The following is a summary of default parameters which have not been hard coded and may be permanently or temporarily changed by users:

1. *Size class longevity* - Staying time for each of the fourteen size classes.
2. *Survival probabilities* - Survival probabilities for all fourteen size classes on actively, seasonally and ephemerally flooded features for each of seven substrate types.
3. *Fecundity* - Numbers of germinants per adult for size classes 5 to 14 for different hydrological events.
4. *Substrate starting proportions* - Site specific substrate starting proportions.
5. *Initial population size* - The area of the site to be modelled, and the numbers of individuals for each size class in that area. Starting density values are automatically calculated.
6. *Density dependence* - The density coefficient (d), for survival and fecundity of all relevant size classes.
7. *Hydrological event weighting* - Weighting factors which determine the influence of poorly understood hydrological events relative to well understood hydrological events.
8. *Discharge range for hydrological states* - The range of discharge ($m^3.s^{-1}$) values for nine

hydrological states (Table 6.1).

Although these parameters may be changed by the user, default values based on best available understanding, are given in the model.

6.12.2 Model Inputs

Before the user can run the model, rainfall and hydrological input files must be loaded, and substrate scenarios selected. Rainfall input file options are either ACRU generated rainfall or user generated rainfall data. Hydrological input file options are either ACRU generated data, user generated data files, or one of various built in scenarios (section 6.3). Substrate type scenarios are either scenarios of predefined increase and decrease of substrate types (section 6.4), or substrate type change that is linked to hydrological events (section 6.4). The model can then be run for a specified length of time or for the maximum number of years for which there are data.

6.12.3 Model Outputs

Once the model has been run for a selected time period, and the output view option has been selected, an output screen opens with three time series graphs (Figure 6.6a): Density of six functional size classes of *B. salicina* (some of which can be logged to toggle resolution between size classes), annual maximum discharge($m^3.s^{-1}$), and substrate proportions.

There are other outputs that users can view: Population size class distributions for any year (Figure 6.6b; from which the shape of the population structure can be determined), a summary of density dependence, actual densities of size classes for any selected year (Figure 6.6b), starting densities of different size classes, the frequency of hydrological states for any selected year (Figure 6.6b), monthly maximum discharges ($m^3.s^{-1}$) for any selected year, detailed information on substrate proportions for any selected year (pie charts for actively, seasonally, and ephemerally flooded substrates) (Figure 6.6b), total annual rainfall for wet and dry seasons of all years, and the results of TPC audits (Figure 6.6c).

An additional aid to interpretation of outputs is a more detailed written summary of the outputs (hydrological events, rainfall, substrate change, fecundity, survival rates, probability of staying) for each year. This output summary (or rule trace) allows the user to observe many of the rules used in the model when interpreting responses.

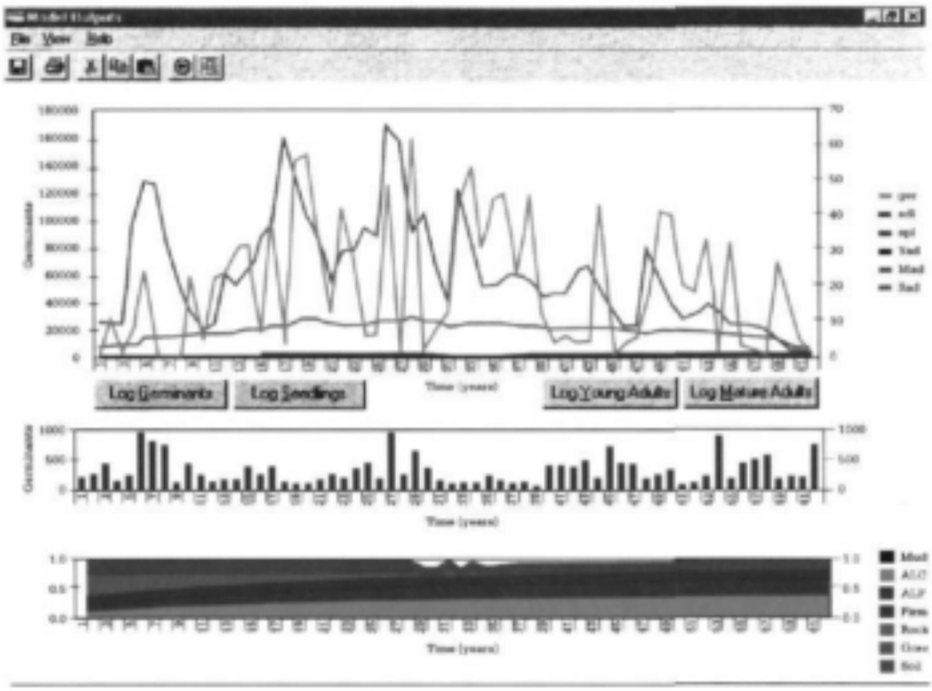

Figure 6.6a. Output screen from the *Breonadia* model showing three time series graphs: Size class densities, annual maximum discharge, and substrate type proportions.

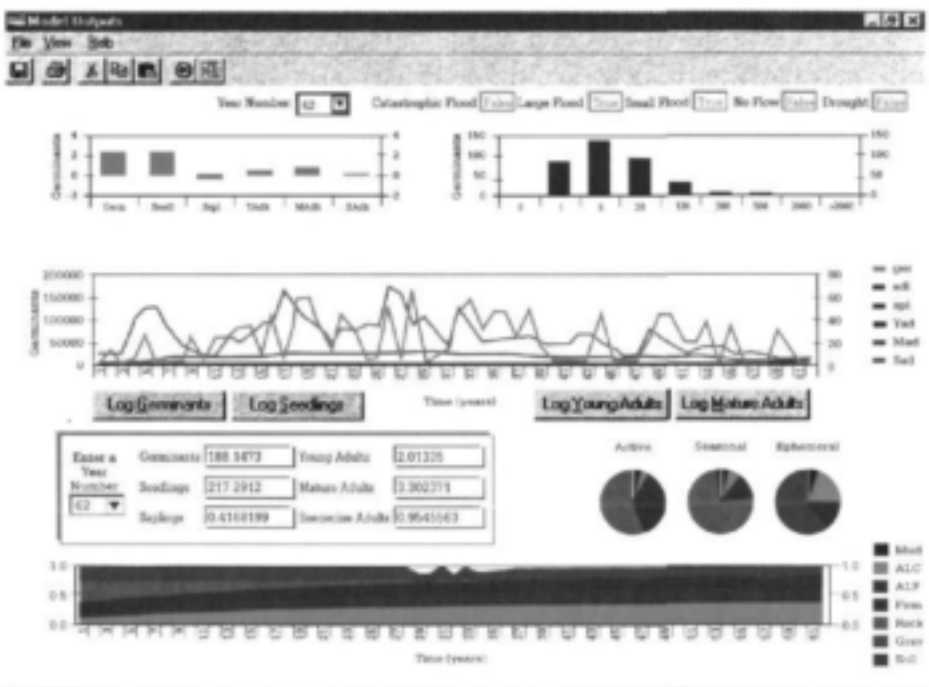

Figure 6.6b. An example of some additional outputs available for viewing for any preselected year: Population structure, occurrence of hydrological status, actual population densities, and proportion of substrates on actively, seasonally and ephemerally flooded features.

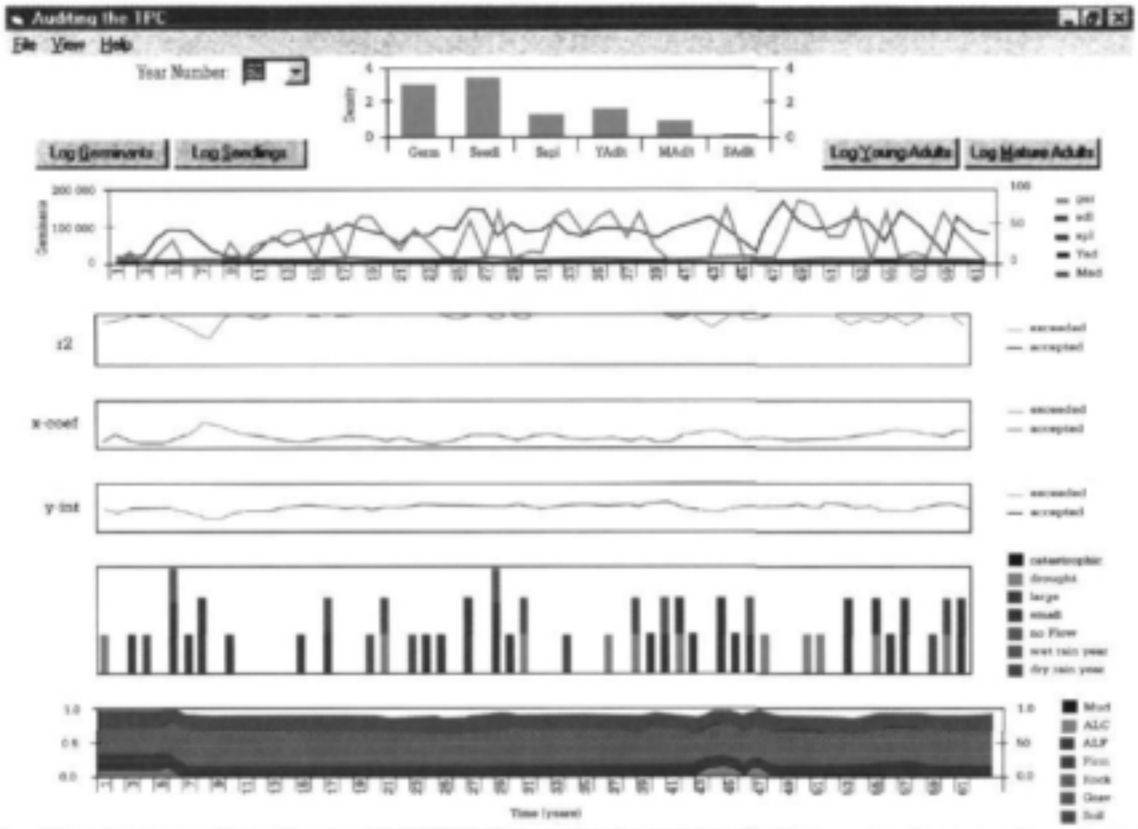

Figure 6.6c. An example of some additional outputs available for viewing for any preselected year: Population structure, occurance of hydrological status, actual population densities, and proportion of substrates on actively, seasonally and ephemerally and flooded features.

Model output after each time step is essentially density of six life history stages (germinants, seedlings, saplings / juveniles, young adults, mature adults, and senescent adults). Population size structure of the latter five size classes forms the basis for evaluation of the TPC (see section 5.4.2). A graph of the population structure can be viewed in the TPC audit screen (Figure 6.6c) where densities have been logged. Since a negative J-shape when logged is a straight line, the shape of the curve can be assessed. Threshold parameters for the TPC are given for those years where they have been exceeded (see chapter 7). TPC acceptance is indicated by a green line for each TPC parameter (r2, x-coefficient, y-intercept) and TPC exceedence by a red line. A TPC protocol is available to assist users to use TPC audits in decision making.

Model outputs can be saved in ASCII format for the user to utilise in other programs should further analyses of output data be required.

6.12.4 Explanatory Notes and HELP

Help facilities have been built into the model to assist users in understanding and utilizing the *Breonadia* model. This includes an introduction to model rationale, information about the structure of the model, guidelines on using the model, and an explanation of the TPC philosophy and how it should be used in the model to interpret results. In addition, there is an explanation of the different input scenarios and default settings used in the model, and how to make changes to these.

Chapter 7

ANALYSIS OF THE *BREONADIA* MODEL OUTPUT

The analysis of the '*Breonadia* model' outputs is dealt with under four sections; (1) validation of the model outputs, setting and evaluation of the TPC, (2) assessment of different scenario outputs, and (4) sensitivity analyses of model parameters and variables.

Validation is the process of assessing correspondence between the output and the rules applied in the model (Starfield *et al.*, 1990).

As discussed in the pervious chapter, thresholds need to be set and evaluated for the loss of bedrock TPC. The model was used to set thresholds. The TPC was then evaluated according to additional outputs of the model.

Testing of the model involves assessing whether the output of the model is a good prediction of what would have occurred in reality under similar circumstances. Usually additional data are used to test the model (Starfield *et al.*, 1990). Since there are at present no data to test the model against, outputs of the model from different hydrological scenarios were assessed relative to current understanding of the species life history characteristics.

An important part of the analysis of the matrix model was to investigate how the results varied in response to changes in parameters and variables of the model. Running a sensitivity analysis provides insight into which of the parameters and variables in the model are important and deserve greater scrutiny.

7.1 VALIDATION

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, fecundity, survival probability of germinants, seedlings, and saplings to senescent adults, and probability of staying in a size class, and checking them against the respective rules applied in the model. ACRU simulated information, including a no flow event and a catastrophic flood, and constant substrate type scenario, were used as the hydrological and substrate type inputs. 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.

7.1.1 Fecundity

The influence of size class, adult density, and hydrological and rainfall events on fecundity were assessed (Figure 7.1). All rules applied in the model for fecundity now comply with their outputs. The most severe reductions in fecundity levels arose from catastrophic floods and no flow events on actively, seasonally, and ephemerally flooded substrates, and droughts on ephemerally flooded substrates had the most severe influence on reducing fecundity levels. While large and small floods also resulted in reduced fecundity on actively and seasonally flooded substrates, there was a marked increase (by a factor of 20 000) in fecundity on ephemerally flooded substrates for large floods. Differences in size class, adult density and dry rainfall years resulted in more subtle decreases in fecundity, while wet rainfall years resulted in an increase.

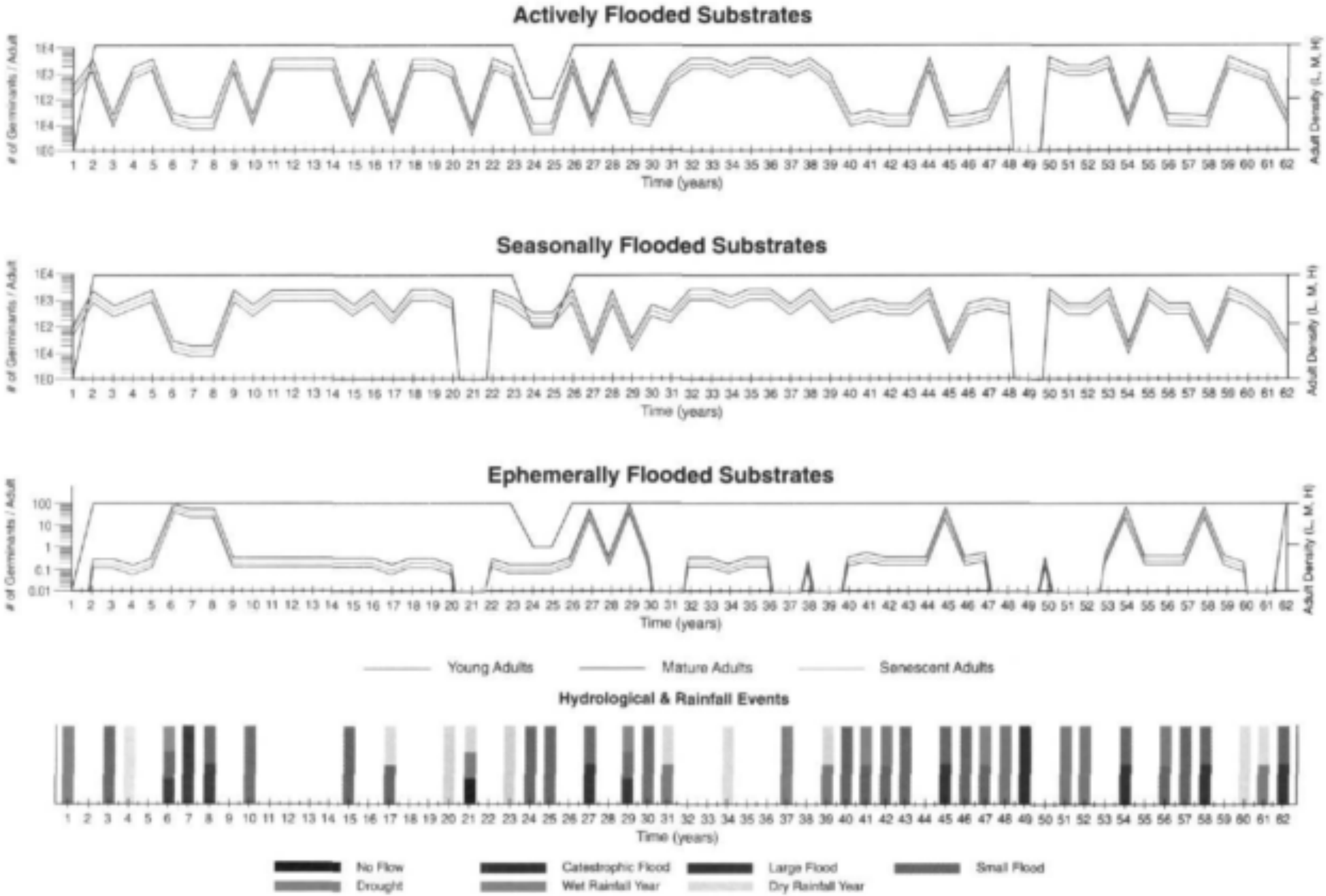

Figure 7.1 Number of germinants produced per adult (fecundity) for young, mature, and senescent adults, on actively, seasonally, and ephemerally flooded substrates for a 62 year period. Fecundity is influenced by, adult density, which is low (L), medium (M), or high (H), and hydrological and rainfall events.

7.1.2 Probability of Survival

The influence of hydrological and rainfall events on survival probability is dependant on size class. Rules applying to probability of survival were validated for germinants, 1st year seedlings, 2nd year seedlings, and saplings to senescent adults.

7.1.2.1 *Germinants*

Substrate type, hydrological events, the timing of hydrological events, and wet and dry periods within a rainfall year, all influence survival probability of germinants (Figure 7.2). All relevant rules were validated and are now correctly applied in the model and give sensible output.

Catastrophic floods, large and small floods between April and December, no flow events, and droughts on ephemerally flooded substrates, all resulted in the marked decrease of germinant survival probability to zero. There was no distinction in survival probability between pril (year 10) and the period of August to December (years 42 and 56). For both small and large floods, the weighting rules used on survival probability for months April to December (see section 6.8.1.1), although correctly applied in the model, do not take affect. This is because the weighting factor is always multiplied by 1 - the probability of removal, which is always equal to zero. This will need to be addressed in further development of the model, so that there is better resolution to the influence of timing on germinant survival.

There were also large differences in germinant survival probability for the different substrate types. On actively flooded substrates, under no event conditions, germinants on rock had the highest probability of survival, followed by germinants on firm alluvium, and then germinants on mud/silt, loose coarse and fine alluvium, gravel, and parent soil. On seasonally flooded substrates, germinants rock also had the highest survival probability, followed by germinants on gravel, and then germinants on firm alluvium, loose coarse and fine alluvium, mud/silt, and parent soil. Probability of survival of germinants was independent of substrate type on ephemerally flooded substrates.

Rainfall periodicity resulted in an increase and decrease in germinant survival probability for wet and dry periods respectively.

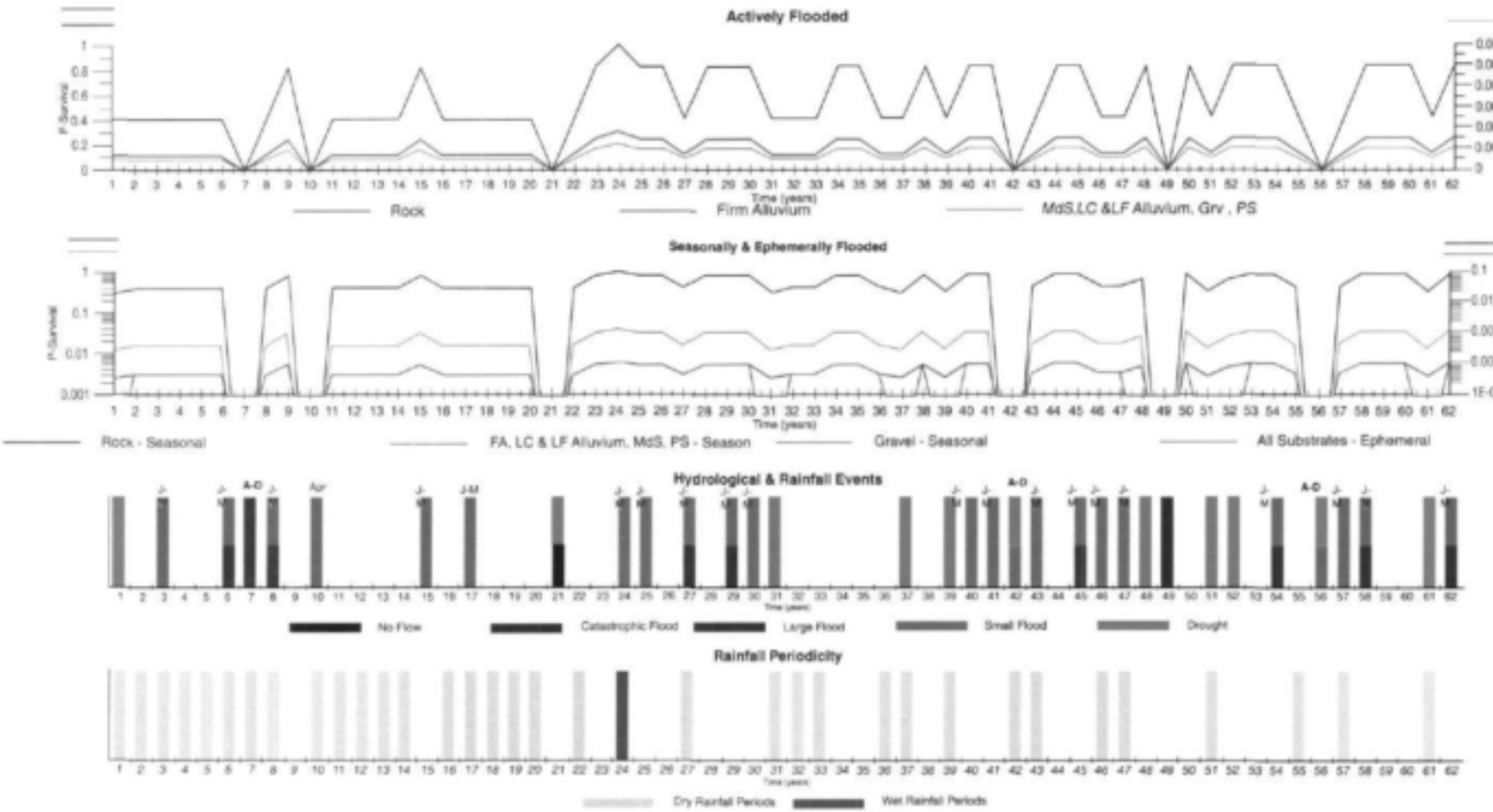

Figure 7.2 Probability of survival of germinants on actively, seasonally and ephemerally flooded substrates for a 62 year run period, using ACRU simulated flow information including a no flow and a catastrophic flood event. Substrate types include bedrock, firm alluvium (FA), loose coarse (LC) alluvium, loose fine (LF) alluvium, gravel (Grv), and parent soil (PS). Probability of survival is influenced by hydrological events, and wet and dry rainfall periods during a rainfall year. Timing of floods occurred during January to March (Jan-Mar), April (Apr), and August to December (Aug-Dec). Substrate type was constant for the 62 year period.

7.1.2.2 First Year Seedlings

The probability of survival of first year seedlings is influenced by substrate type, hydrological events and wet and dry periods during a rainfall year (Figrue 7.3). All relevant rules were validated and are now correctly applied in the model.

No flow events had the most negative influence on 1st year seedling survival by decreasing their probability to zero.

In contrast, floods resulted in both an increase and a decrease in survival probability. Due to the rate of increase being built into the response of 1st year seedlings (see section 6.8.2.(ii), table 6.4) to small, large, and catastrophic floods, survival probability in many cases exceeded the value of one. Probability of survival in its strictest sense will never be more than one, but for the purposes of the model, 1st year seedling survival probability was allowed to exceed one.

Catastrophic and large floods both resulted in increases in survival probability on actively and seasonally flooded bedrock, and decreases in survival probability on actively flooded firm alluvium and seasonally flooded gravel. On ephemerally flooded substrates, however, catastrophic floods resulted in an increase in survival probability for all substrate types, while large floods did not influence survival probability. Small floods resulted in an increase in survival probability on actively flooded bedrock and firm alluvium, and seasonally flooded bedrock, and a decrease in survival probability on seasonally flooded gravel.

Rainfall periodicity acted to either decrease or increase survival probability (by 0.25), if dry or wet periods respectively, occurred in a rainfall year.

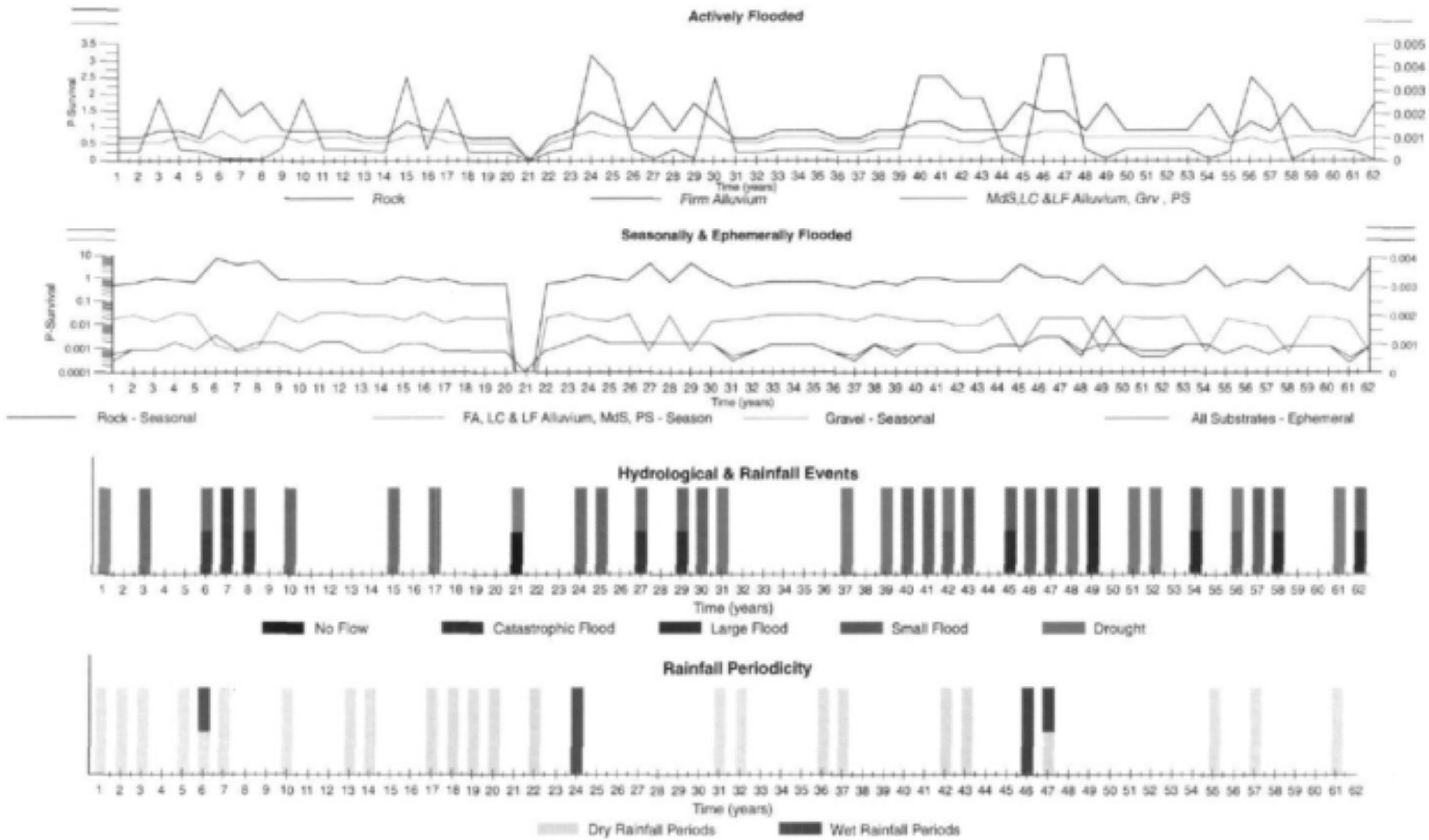

Figure 7.3 Probability of survival of 1st year seedlings on actively, seasonally and ephemerally flooded substrates for a 62 year run period, using ACRU simulated information including a no flow and a catastrophic flood event. Substratetypes include bedrock (rock), firm alluvium (FA), loose coarse (LC) alluvium, loose fine (LF) alluvium, gravel (Grv), and parent soil (PS). Probability of survival is influenced by hydrological events, and wet and dry rainfall periods during a rainfall year. Proportion of each substrate type was constant for the 62 year run period.

7.1.2.3 Second Year Seedlings

Survival probability of 2nd year seedlings is influenced by substrate type, hydrological events, and wet and dry rainfall periods within a year (Figure 7.4). All relevant rules were validated and are now correctly applied in the model. Unlike 1st year seedlings, survival probability of 2nd year seedlings is not influenced by rate of increase following a small, large or catastrophic flood. Survival probabilities are therefore always less than or equal to one.

No flow events, and large and catastrophic floods, all resulted in a zero survival probability for all inundation frequencies and substrate types. The influence of small floods was not as dramatic, but still resulted in a decrease in survival probability on all substrate types and inundation frequencies. In contrast, droughts did not influence survival probability on actively flooded substrates. They did however, decrease survival probability on seasonally and ephemerally flooded substrates.

On actively flooded substrates, survival probability was highest on bedrock, then firm alluvium, and then the remaining five substrate types. On seasonally flooded substrates, survival probability was highest on bedrock, then gravel, and then the remaining five substrate types. Survival probability on ephemerally flooded substrates was not influenced by substrate type.

Seedlings showed the same response to wet and dry rainfall periods in their 1st and 2nd years.

7.1.2.4 Saplings to senescent adults

The probability of survival of saplings to senescent adults is influenced by, hydrological events, and dry rainfall years (Figure 7.5). All relevant rules have been validated and are presently correctly applied in the model and produce output compatible with current understanding.

Survival probabilities of all size classes were most influenced by no flow events. For the other hydrological and rainfall events there is a trend of decreasing importance of flooding, and an increase in importance of droughts and dry rainfall years from saplings to senescent adults. Survival probability of saplings, decreased most in response to catastrophic and large floods, while survival probability

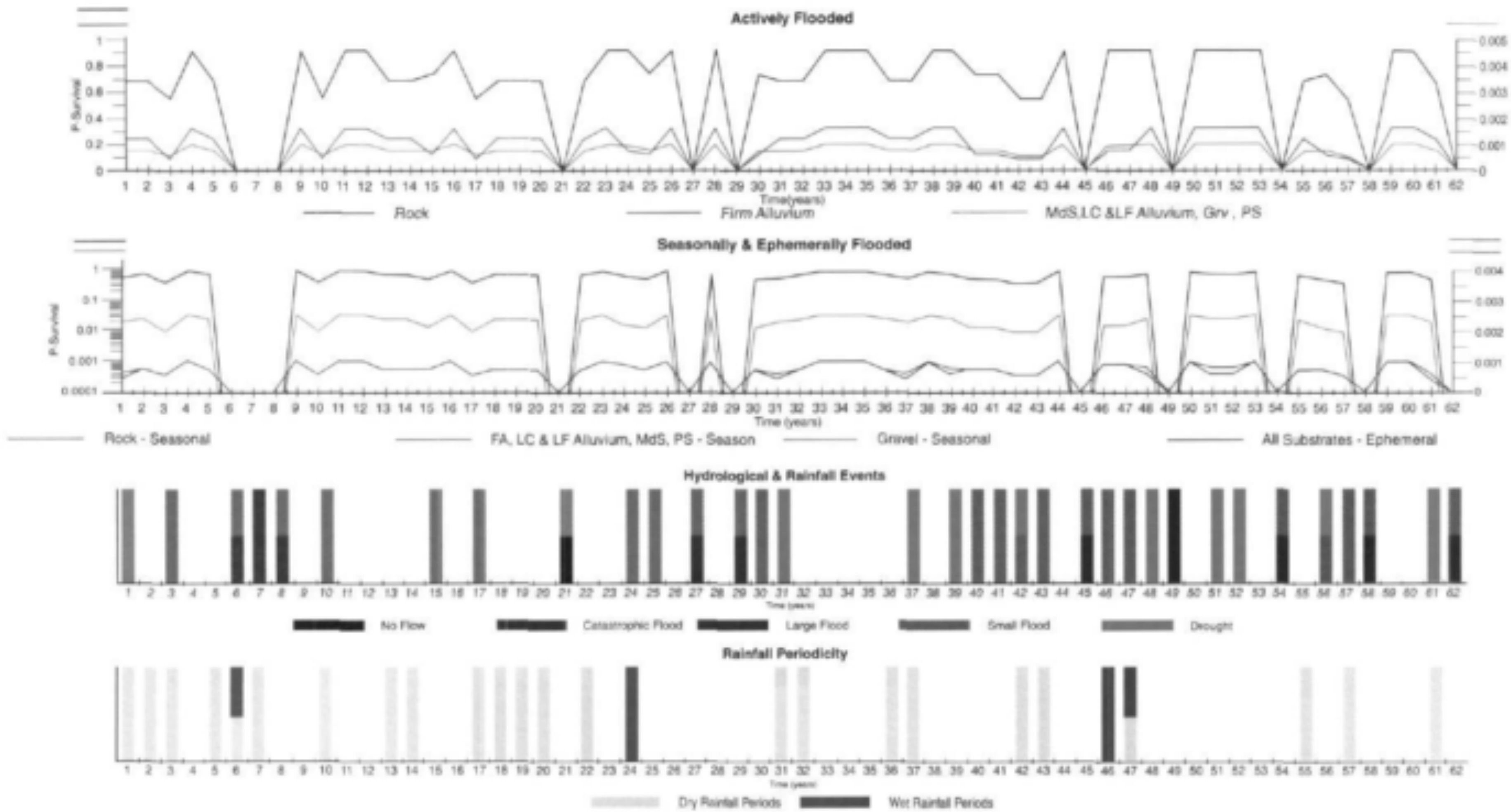

Figure 7.4 Probability of survival of 2nd year seedlings on actively, seasonally and ephemerally flooded substrates for a 62 year run period, using ACRU simulated flow information including a no flow and a catastrophic flood event. Substrate types include bedrock (rock), firm alluvium (FA), loose coarse (LC) alluvium, loose fine (LF) alluvium, gravel (Grv), and parent soil (PS). Probability of survival is influenced by hydrological events, and wet and dry rainfall periods during a rainfall year. Proportion of each substrate type was constant for the 62 year run period.

of mature and senescent adults decreased most in response to droughts and dry rainfall years.

On actively flooded substrates, where droughts had no influence on mature and senescent adult survival probability, dry rainfall years were most important. Decreases in survival probability following hydrological or rainfall events, were always greatest for saplings, and least for senescent adults.

Survival probabilities of saplings to senescent adults were independent of substrate type.

7.1.3 Probability of Staying

Probability of staying in a size class is influenced by hydrological events of no flow, catastrophic floods, large floods, and small floods (Figure 7.6). The influence of these events is independent of inundation frequency (i.e., actively, seasonally, or ephemerally flooded) and substrate type.

The main influence on staying probability was for no flow events which increased staying probability of all age classes to one. In contrast, germinant and seedling staying probabilities were not influenced by flooding, and always had a zero rating. Saplings to senescent adults all showed an increase in probability of staying with an increase in severity of flood events, but young and mature adults responded more acutely than saplings and senescent adults. This is due the probability of damage being highest in young and mature adults (see Figure 7.6).

7.2 SETTING AND EVALUATION OF THE TPC

7.2.1 Setting thresholds

An objective means of testing whether the TPC has been exceeded is critical to the use of the model by managers. As discussed in the previous two chapters, the TPC for the '*Breonadia* model' is based on a negative J-shaped population structure for all non-germinant size classes, as this represents the degree of bedrock influence. Clear parameters need to be applied to the shape of the curve if interpretation of population structure is to be objective.

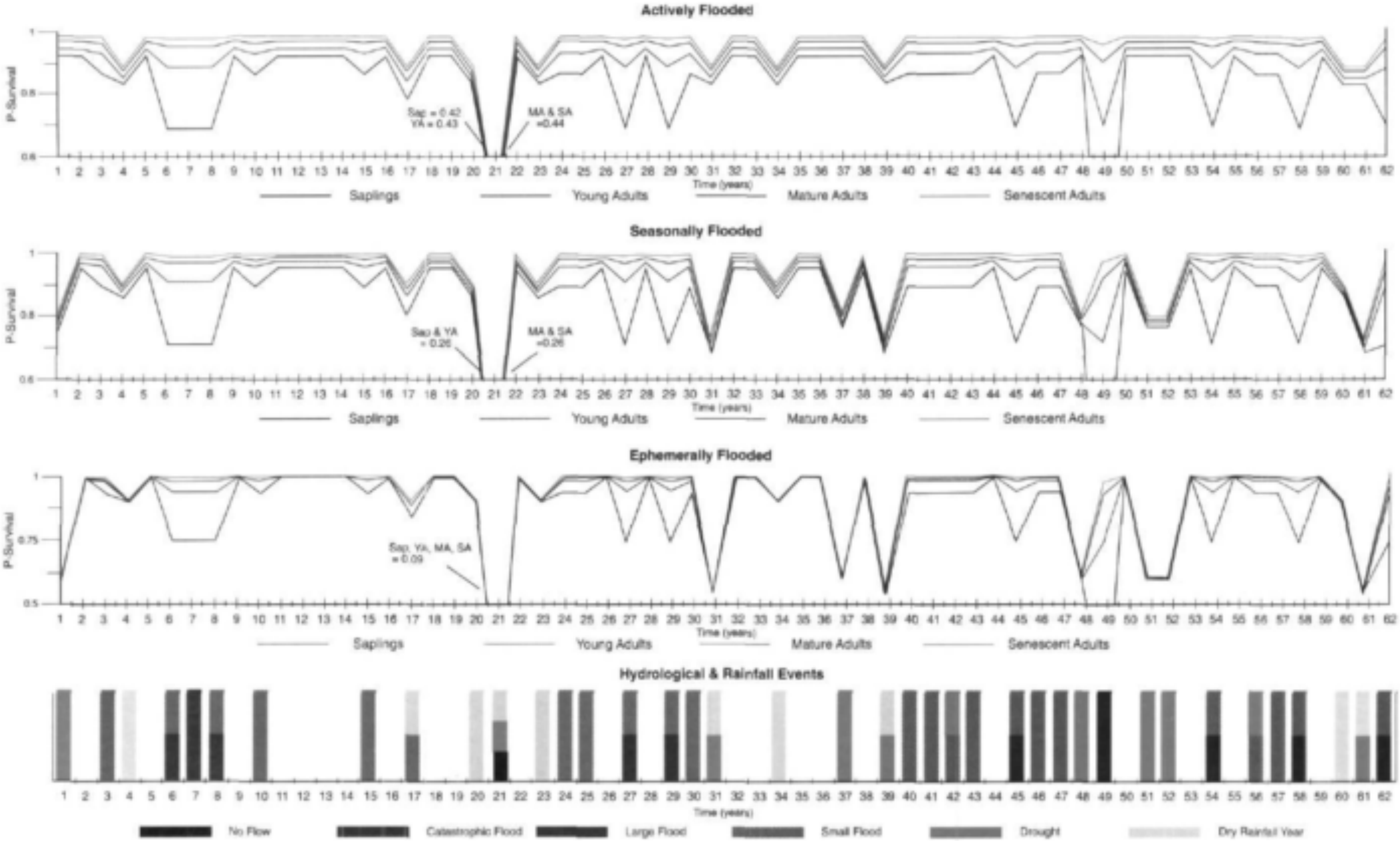

Figure 7.5 Probability of survival of saplings (Sap), young adults (YA), mature adults (MA) and enescent adults (SA) on actively, seasonally and ephemerally flooded substrates, during a 62 year run using ACRU simulated information including a no flow and a catastrophic flood. Probability of survival is influenced by hydrological events and dry rainfall years. Proporton of each substrate type is constant for the 62 year run period.

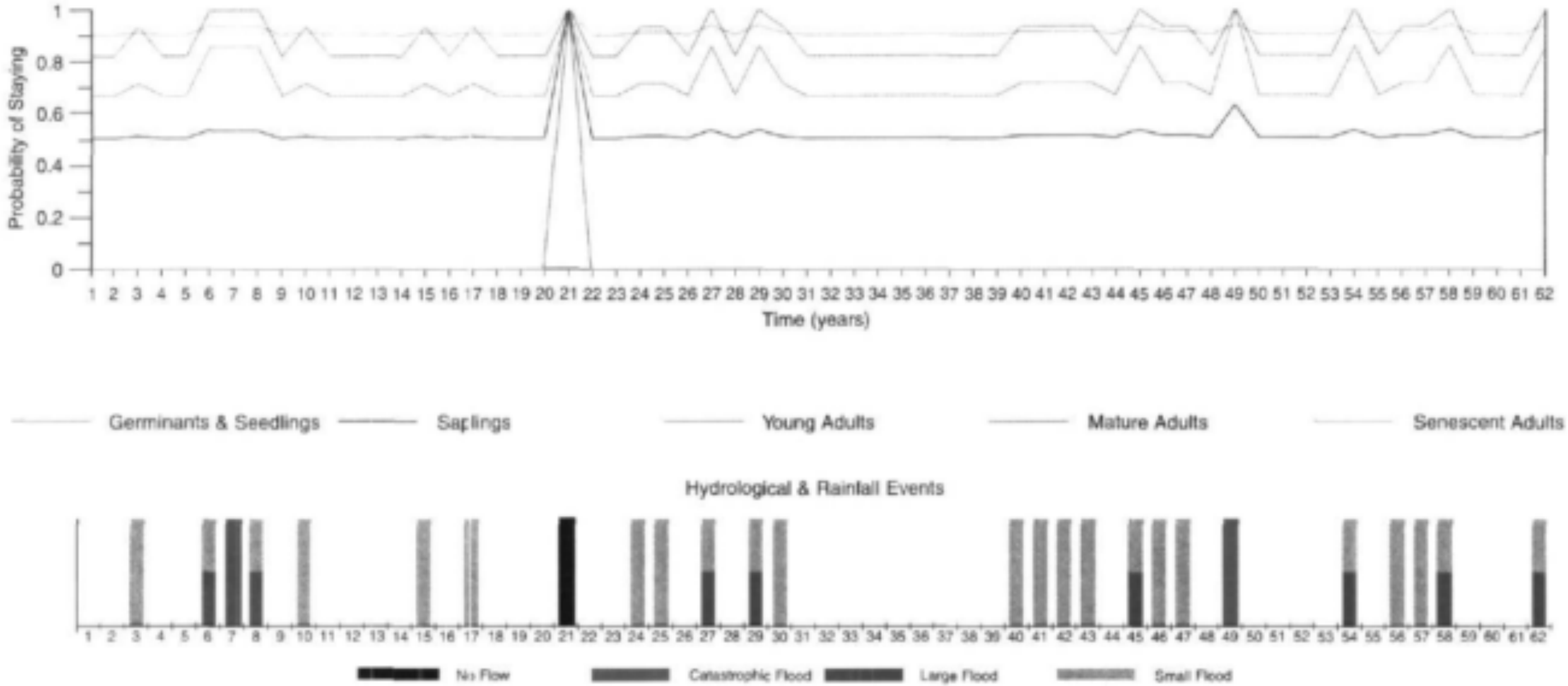

Figure 7.6 The probability germinants, seedlings, saplings, young adults, mature adults and senescent adults staying in a size class for a 62 year run time using ACRU simulated information and a constant substrate scenario. Probability of staying is influenced by hydrological events of no flow, catastrophic floods, large floods and small floods.

Three components of the shape of the curve were selected as being biologically important;

(1) the degree of fit to a negative J-shape,

(2) the steepness of the curve (i.e., the relative densities of the smaller size classes compared to the larger size classes), and

(3) the average densities of the different size classes (low average densities indicate an unhealthy population).

A simple method was used to determine parameters for these three components. Densities of the different size classes were firstly logged, since a negative J- shape curve when logged generates a straight line. Linear regression was then applied to determine the degree of fit (the r^2 value), the slope of the curve (the x-coefficient), and the average densities of the population size classes (the y intercept or constant). Thus, the three parameters used to interpret the shape of the population structure are;

(1) the r^2,

(2) the x-coefficient, and

(3) the constant.

Thresholds needed to be set for these three parameters. At present, data for determining these thresholds are not adequate. The model has therefore been used to provide first estimates from a scenario of declining bedrock and increasing loose coarse and fine alluvium, accompanied by a hydrological scenario of progressively declining flow.

The values obtained for each of the three parameters at a point when bedrock reaches critically low levels, could form the threshold. It was important that a realistic value be selected to represent a critically low bedrock proportion. The TPC is concerned with rapid sections of pool-rapid channel types. Two transects perpendicular to the river that passed through rapid sections were the best available data to determine a value for a critical bedrock proportion (van Coller unpublished data). One transect had 23% of the area covered by bedrock, while the other had 8 % of its area covered by bedrock. The latter transect showed a low degree of bedrock influence with substantial sedimentation. We therefore use this transect as a rough guide of a critically low level of bedrock influence. A value of 7% or less bedrock was selected as a critical level of concern. It must be emphasized that this value is a first estimate, and is open to change when better data become available.

Bedrock proportion dropped below 7 % in year 35 (Figure 7.7). Coincidentally, there were no hydrological or rainfall events in year 35, thus providing a year where the shape of the population structure was not confounded by any events. The values of the three parameters at year 35, were used as threshold values;

(1) $r^2 = 0.926$,

(2) x-coefficient = -0.68, and

(3) constant = 4.04.

Exceeding the threshold of one of these parameters, represents transcendence of the TPC. This provided a basis for identifying years where the TPC might have been exceeded.

It is important to highlight that these thresholds are first estimates generated by the model, and should not be treated as final values. Refinement of these values will occur following collection of additional data through monitoring and testing of the model with field data. The process by which these thresholds are altered will follow the iterative process described in section 5.2 (Rogers & Biggs, 1999).

7.2.2 Evaluation of thresholds

The model run is used to evaluate the conditions under which the parameters of the TPC are exceeded, and how these parameters change in response to environmental scenarios. This evaluation provided the basis for a protocol for use of the TPC in the field and future monitoring to be developed.

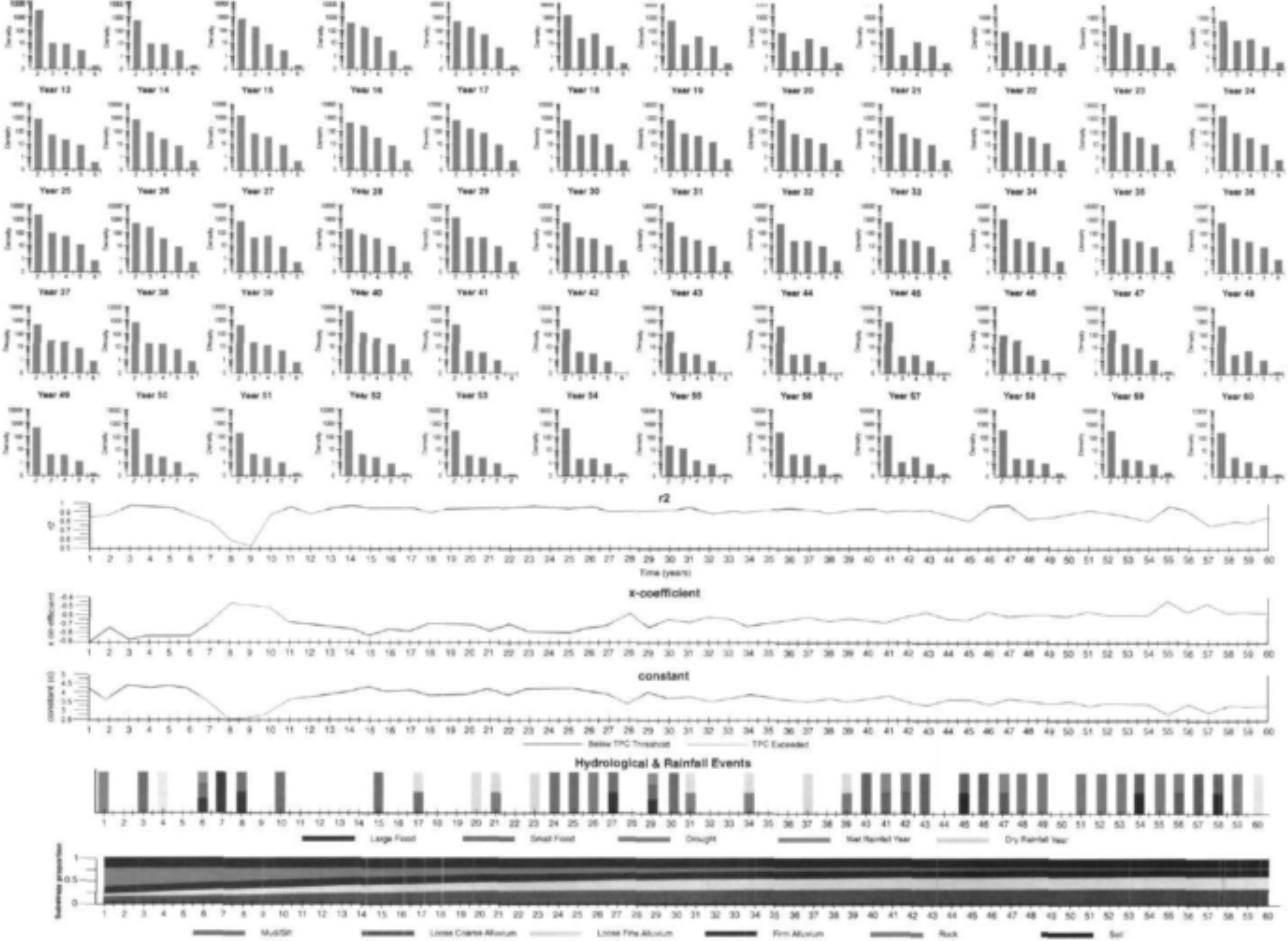

Figure 7.7 Population structures of Breonadia salicina, showing densities of seedlings (2), saplings (3), young adults (4), mature adults (5) and senecent adults (6) on a log scale, for each year of a 60 year run period, using a scenario of progressive decline in flow and bedrock proportion. Thresholds of exceedence are shown for the TPC parameters of r^2 (0.926), x-coefficient (-0.68) and constant (4.04) for the 60 year run. Hydrological and rainfall events and change in substrate type proportion influence the population structure.

It is evident that the TPC is exceeded for years subsequent to year 35 as bedrock continues to decline, (Figure 7.7), thus confirming that the model predicts a loss in the negative J-shape curve as bedrock influence declines. The value of having more than one parameter to assess the shape of the population structure was demonstrated by years 46, 47, and 55. Although the r^2 values for these three years are all high and below the TPC thresholds, the slope and the y-intercept both exceed the TPC thresholds. Thus, even if the population structure has negative J-shape curve, the slope of the curve may be too shallow (too few germinants and seedlings relative to adults) or the average densities of the size classes (indicated by the constant) may be too low.

The TPC was also exceeded in a number of years prior to year 35 where there was a healthy proportion of bedrock influence. Since bedrock influence for these years was not at critically low levels, it is important to carefully examine the years where the TPC was exceeded.

Years 1and 2 - Exceedence of the r^2 value for these years is likely a consequence of the starting values of the population in the model, and should be ignored as years of concern.

Years 6 to 12 and 27 to 31 - Exceedence of the TPC for all three parameters for these years can be directly correlated with large floods in years 6, 7 and 8, and years 27 and 29 and a time of recovery from years 9 to 12, and years 28, and 30 to 31. Thus, although the TPC was exceeded, these years should not be treated as an immediate concern, since there was a good level of bedrock influence, and large floods appeared to be the causal factor. If, however, the TPC continues to be exceeded for more than two years after each large flood event, then the cause of the TPC being exceeded should be reexamined.

Years 32 to 34 - Besides a drought and dry rainfall year in year 34, no events occur to result in the TPC being exceeded. Since droughts or dry rainfall years do not have a marked influence on the shape of the population structure any other years, it is likely that these three years are rather an early warning of the loss of bedrock influence, and thus should be accepted as years of concern.

Year 18 - Exceedence of the r^2 parameter in year 18 cannot be related to any hydrological events and bedrock influence is high. If the year following year 18 also exceeds any of TPC parameters, and there are no obvious reasons, then it is necessary to reevaluate the TPC. Since this is not the case, year 18 is not treated as a year of concern.

The influences of catastrophic floods and a no flow event on the shape of the population structure were tested in a separate run of the model, where substrate type was kept constant and bedrock was in high proportions (0.44). The results show that for both events, the shape of the population structure is dramatically altered and all three TPC parameters are exceeded (Figure 7.8). In the years following both events, there is period of recovery before the shape of the population structure falls below the TPC. A period of at least four years of recovery is required, for both a no flow event and a catastrophic flood (Figure 7.8). In both cases, the year of the event, as well as the recovery years should be taken into account when evaluating the TPC.

Evaluation of the TPC from these model runs provides guidelines for the development of a formal TPC protocol. This has been summarized in the form of a decision support tree (Figure 7.9). TPC values for a monitored year or predicted model output are assessed in the context of hydrological events. The outcome of the protocol is that either the TPC is rechecked x years later, reassessed or management action is taken via a decision support system.

7.3 SCENARIO OUTPUTS

Outputs from different flow scenarios were assessed as an alternative form of testing the model. The questions asked were, are the outputs of the model what would be expected based on a general understanding of the species, and do they highlight any inadequacies in the model? Three different types of scenarios were used for the assessment, namely, a natural flow, a recommended maintenance IFR flow scenario at the Skukuza IFR site (Tharme 1997), and a constant flow scenario of 5.4 $m^3.s^{-1}$ for every day of the year.

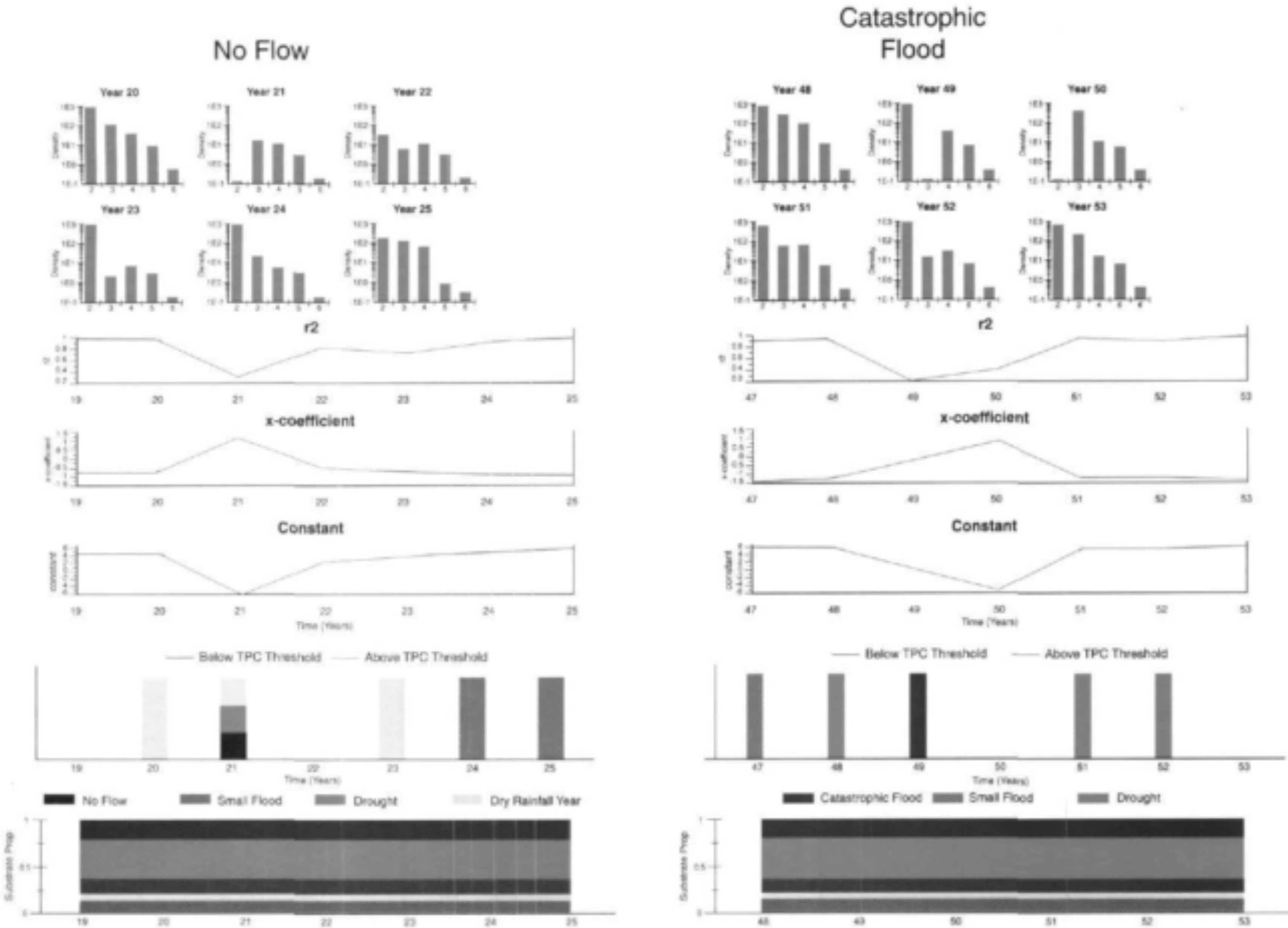

Figure 7.8 The influence of a no flow event and catastrophic flood on the population structure of *Breonadia salicina* and thus the TPC values for the three parameters of r², x-coefficient, and constant. Substrate type proportion is unchanging and bedrock proportion is high (0.44).

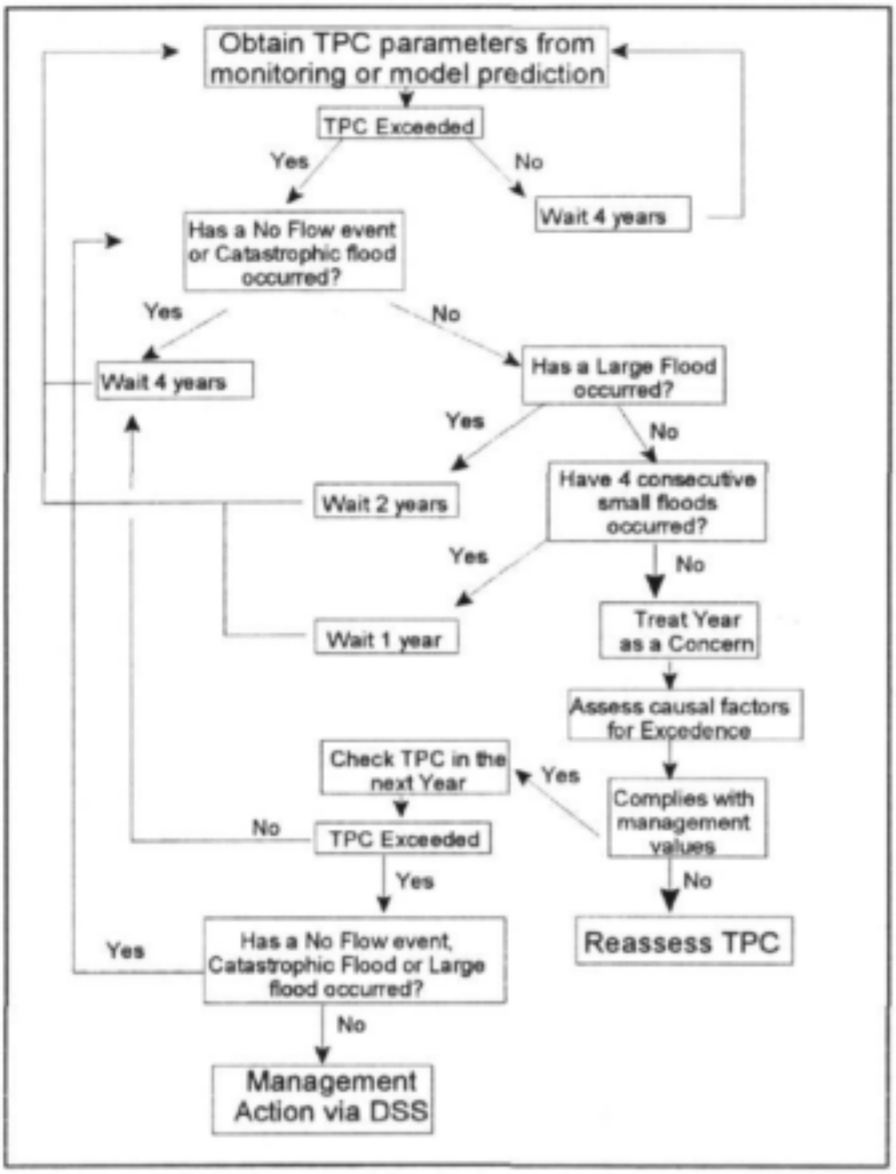

Figure 7.9 A formal protocol for the loss of bedrock influence TPC in the form of a decision tree.

Substrate change for all scenarios was based on the substrate type - hydrology link. The same default settings were used for each scenario so that comparisons between scenarios are valid.

7.3.1 Natural Flow

A run using ACRU simulated information was used as the hydrological input to simulate a natural flow uninfluenced by dams or any other catchment practices (Figure 7.10).

Change in the substrate type under natural flow conditions would be expected to maintain a good level of bedrock influence, with no overall increase or decrease in sediment storage taking place. The output of the substrate type - hydrological link confirmed this, where the average bedrock proportion did not change between the first and last 31 years (both 50 %) for the 62 year period (Figure 7.10). Bedrock proportion, however, fluctuated between 43 and 55 % as a result of increases brought about by large and small floods, and decreases brought about by droughts.

An expected population response to a natural flow and maintenance of a good level of bedrock influence, would be that all size classes show dynamic fluctuations in response to hydrological and rainfall events, and that there is no overall increase or decrease in the densities of all size classes with time due to no overall change in bedrock influence.

The smaller size classes of germinants, seedlings and saplings all display dynamic shifts in their densities in response to hydrological and rainfall events. Unexpectedly however, all three size classes showed trends of increase over the 62 year run period. Comparison of the average densities for the first and last 31 years, showed that germinants had a greater increase (50%) than seedlings and saplings (17 and 22%) over the 62 year period. As would be expected there is a decrease in the degree of fluctuation in densities from young adults to senescent adults. The larger three size classes, however, also showed an overall trend of increase in density for the 62 year run period, indicating that they have not attained equilibrium. Senescent adults showed a markedly higher increase in average density (108%) than young and mature adults (33 and 30 % respectively) from the first 31 years to the last 31 years. The unexpected increases in densities shown by all size classes, especially senescent

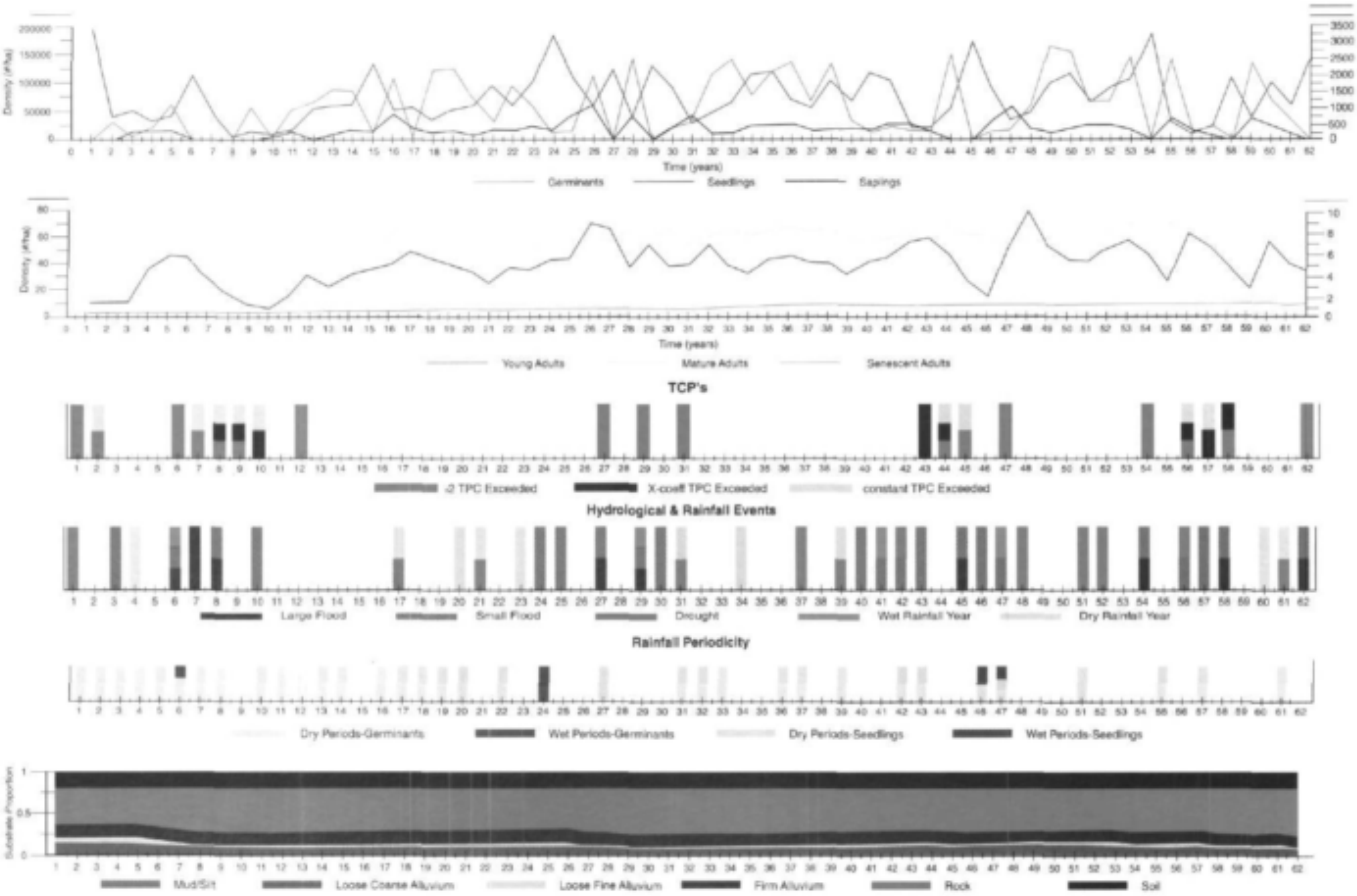

Figure 7.10 Response of the different size classes of the *Breonadia salicina* population to ACRU simulated flow information, and change in substrate type proportion according to the substrate type - hydrology link scenario. Years where the TPC parameters are exceeded are shown, along with hydrological and rainfall events, rainfall periodicity, and change in substrate type proportion.

adults and germinants, suggests that density dependence values are too low. The extremely high increase observed for senescent adults may also be due to longevity being too high. Both these parameters need to be checked in future monitoring programmes.

Since bedrock influence is high throughout the run time, TPCs should only be exceeded when large floods occur and there is a recovery period. In nearly all cases, the TPC is exceeded for years where there are large floods (years 6 to 8, 27, 29, 45, 54, 58 and 62)and recovery periods following the large flood (year 9 to 12, 31, 47 and 56), or years 1 and 2. There are some years however (years 43, 44 and 57), where there is no clear reason why the TPC has been exceeded. For year 57, it is likely that the population is still recovering from the large flood in year 54, even though it is three years after the event. The only possible explanation for why years 43 and 44 have exceed the TPC, that was not evident when evaluating the TPC (section 7.2.2), is that there are four consecutive years of small floods occurring from years 40 to 43. It is very possible that their accumulated influence resulted in the loss of a healthy negative J-shape population structure. The influence of small floods, therefore also needs to be incorporated into the TPC protocol (Figure 7.9), where if the TPC has been exceeded following four consecutive years of small floods, then a year of recovery should be allowed before assessing the TPC

The output of the model using a natural flow scenario, thus, showed that overall dynamics responded to events as expected, but that density dependence of all size classes, and longevity of senescent adults were likely to be incorrect. It also highlighted the need to incorporate small floods into the TPC protocol.

7.3.2 Maintenance IFR

The purpose of assessing the maintenance IFR scenario (Figure 7.11) is to determine if the recommended IFR flows released from a dam with no overtopping flows, maintain a 'healthy' *B. salicina* population.

It has been shown from a flow sediment simulation model (Birkhead *et al.* in press) that under IFR flows there will be progressive sedimentation of the Sabie River. The results of the *Breonadia* model output show that according to the substrate type - hydrology link, substrate type proportion over the 62 year period does not change. This is a result of no hydrological events (i.e., no flow events, small floods, large floods, catastrophic floods, and droughts) occurring in the model for the maintenance IFR scenario, since the highest flows are 180 $m^3.s^{-1}$ and no droughts occur. The need to greatly improve the substrate type - hydrology link is thus highlighted.

An expected response to an increase in sedimentation in the population would an overall decrease in the densities of all size classes and a loss of a healthy negative J-shaped curve (as shown in Figure 7.7). However, since substrate type did not change over the 62 year period, the densities of the different size classes would be expected to reach some form of dynamic equilibrium in the model output. In addition, since no hydrological events occur in the model under a maintenance IFR scenario, the dynamics in the densities of each size class would be expected to be far less than under a natural flow scenario (Figure 7.10), since the population only responds to rainfall.

The results confirm that fluctuations in population density are largely in response to rainfall events and periodicity, and are far less dynamic (Figure 7.11) than the outputs from the natural flow scenario (Figure 7.10).There is a need to include rules of response to events arising from lower flow hydrological states. Despite bedrock influence remaining unchanged for the 62 year run period, germinants, seedlings, saplings, young adults, mature adults, and especially senescent adults all show increased in average density (45, 12, 23, 18, 19, and 166 % respectively) between the first and second 31 years, indicating that they have not reached equilibrium. The same explanation for the increases in density observed under a natural flow scenario is likely to be true. The much higher increase in the senescent adults under a maintenance IFR compared to a natural flow scenario is a result of no droughts occurring, which do not result in a decrease in their survival probability.

When bedrock influence is high and no hydrological events occur throughout the run time, and population levels were expected to reach equilibrium, the TPC should never be exceeded. The much higher increase in density of senescent adults relative to all other size classes however will result in

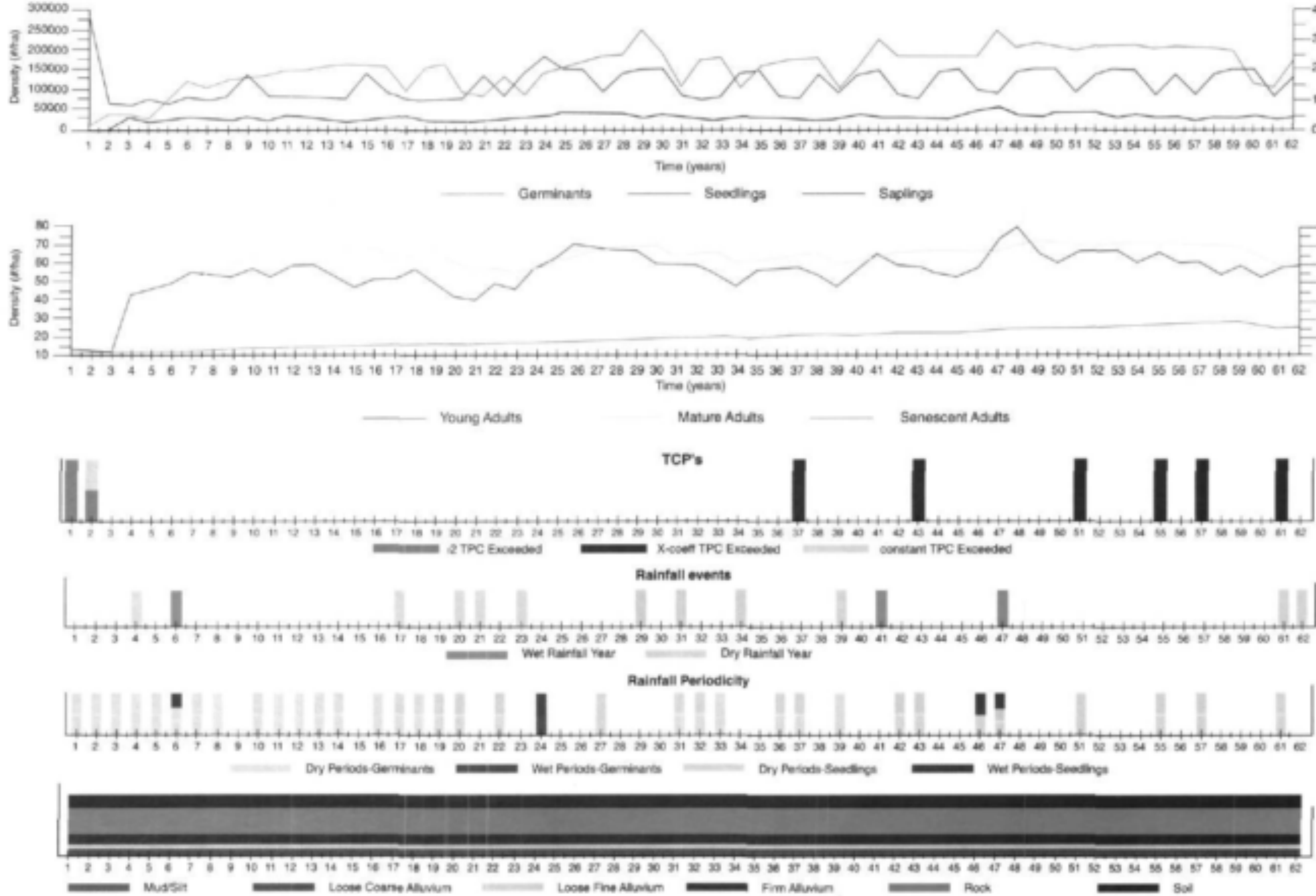

Figure 7.11 Response of different size classes of the *Breonadia salicina* population to maintenance IFR flow scenario at the Skukuza IFR site, and change in substrate type proportion according to the substrate type - hydrology link scenario. Years where the TPC parameters are exceeded are shown, along with hydrological and rainfall events, rainfall periodicity, and change in substrate type proportion.

a flattening out in the curve of the population structure. This was confirmed by the x-coefficient parameter being regularly exceeded for the last twenty years. This demonstrates the usefulness of using three TPC parameters instead of one to describe the population structure.

The results from the maintenance IFR scenario highlighted three areas of inadequacy in the model. (1) The need to improve the substrate type - hydrological link, (2) improvement on the estimation of density dependence of all size classes and longevity of senescent adults, and (3) the need to translate hydrological states of extreme low flows, base flows, intermediate flows, high flows and very small floods into events that result in a population response.

7.3.3 Constant flow release of 5.4 $m^3.s^{-1}$

A constant flow scenario was run to determine the influence of eliminating all variability from the flow regime. A daily flow of 5.4 $m^3.s^{-1}$ was used, as it is equal to the total annual IFR at the Skukuza site averaged for each day of the year.

It is likely that a constant flow scenario and a maintenance IFR scenarios will result in very different population responses in the field, since in one scenario there is no variability while in the other flow varies between 3 and 180 $m^3.s^{-1}$. In the model, however, the two flow regimes resulted in identical events influencing the *B. salicina* population in the model (Figures 7.11 and 7.12). No hydrological events take place and the population only responds to rainfall because model rules do not yet distinguish extreme low flows, base flows, intermediate flows, and very small floods as separate events to which the population responds. Since the events for the two scenarios are identical, the substrate change, population response and TPC outputs should also be identical, and were (Figures 7.11 & 7.12).

An improved understanding of population response to the full range of low and intermediate flows would improve the model.

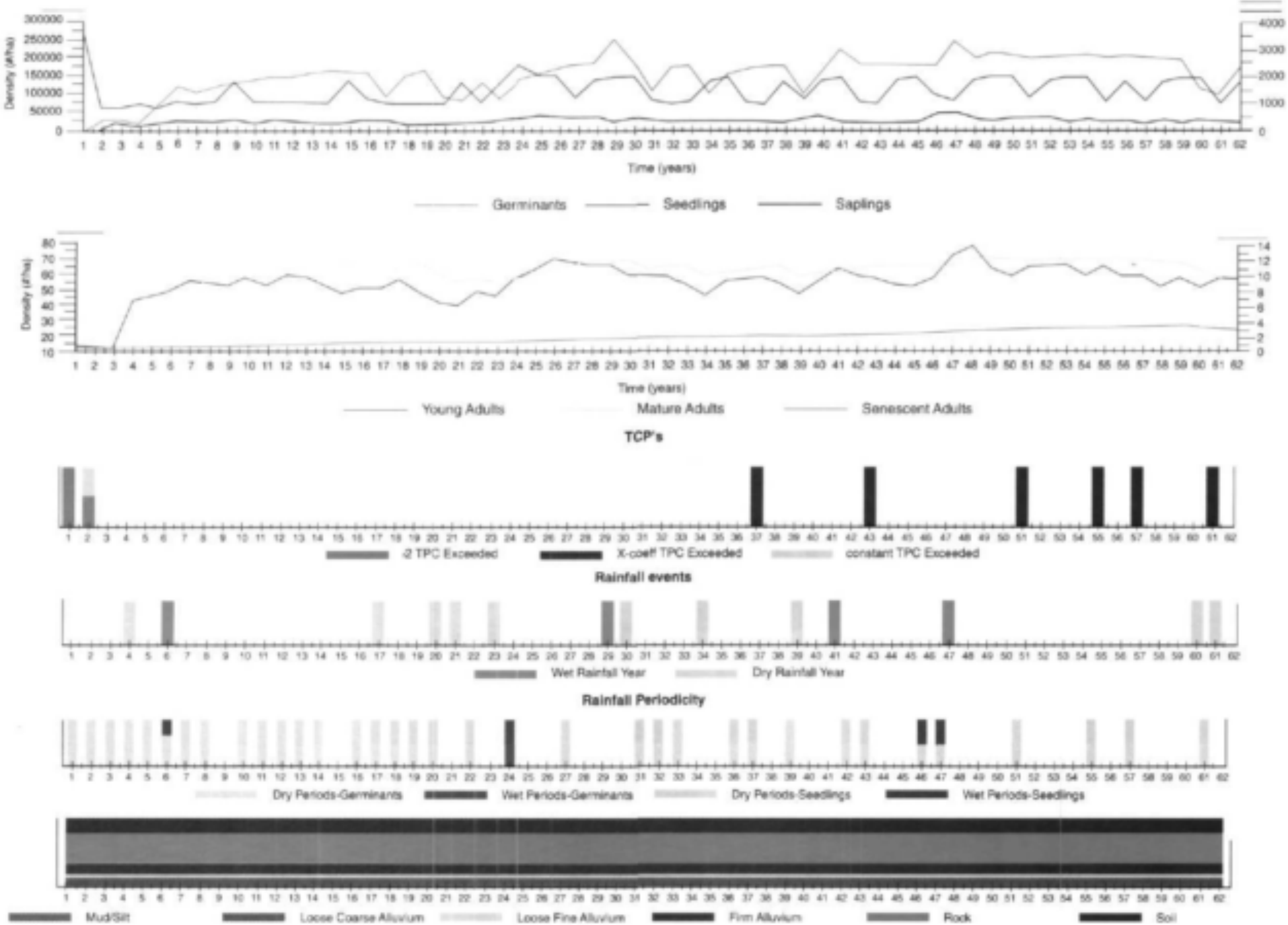

Figure 7.12 Response of different size classes of the *Breonadia salicina* population to a constant annual flow of 5.4 $m^3.s^{-1}$, and change in substrate type proportion according to the substrate type - hydrology link. Years where TPC parameters are exceeded are shown, along with hydrological and rainfall events, rainfall periodicity, and change in substrate type proportion.

7.4 SENSITIVITY ANALYSIS

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

7.4.1 Parameter sensitivity

In a sensitivity analysis, parameters are systematically changed to determine their effect on the output (Starfield & 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 & 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 multiplying each parameter by factors of 0.25, 0.5, 1.5 and 2. It was not always possible to use these factors for all parameters. For example, a nominal survival probability of 0.967 cannot be meaningfully multiplied by factors of 1.5 or 2, 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. A negative and positive value indicated the same level of sensitivity (e.g., an S-value of 0.379 and -0.379), and were therefore treated as the same value.

The following parameters were used in the sensitivity analyses, which resulted in over 850 model runs of 62 years each:

- Size class longevity for each of 14 size classes
- Survival probabilities for each of 14 size classes on 7 different substrate types for active, seasonal and ephemeral geomorphological features
- Fecundity for no event and large flood scenarios on active, seasonal and ephemeral geomorphological features
- Initial population size for each of 14 size classes
- Area of the site being modelled
- Small and catastrophic flood factors
- Hydrological event weighting effects on fecundity for droughts, no-flow, small floods and catastrophic floods on active, seasonal and ephemeral geomorphological features
- Density dependence effects on survival for each of 14 size classes
- Density dependence effects on fecundity for young, mature and senescent adults
- Hydrological states
- Total rainfall effects on fecundity in the wet season
- The frequency of the presence and absence of defined, continuous rainfall periods for the survival of germinants and seedlings
- An increase in seedling numbers after floods
- Substrate starting proportions: 70 possible combinations with 2 parameters each

Single parameter sensitivity analyses were not possible for substrate starting proportions because as one increased, so another had to decrease for all values to sum to 100%. Multiple sensitivity analyses were therefore used for substrate starting proportions with only two parameters being changed at a time, and using all possible combinations. The sensitivity index for multiple parameter analysis (S) is given by:

$$S = \frac{\frac{R_a - R_n}{R_n}}{\sqrt{(p_1 - p_1^{\prime})^2 + (p_2 - p_2^{\prime})^2}}$$

where p_1 and p_2 are nominal parameters and $p_1^{\prime}$ and $p_2^{\prime}$ are altered parameters (Haefner, 1996).

7.4.2 Results

The sensitivity index for the 50 most sensitive parameters is shown in Tables 7.1, 7.2, 7.3, 7.4, 7.5 and 7.6 for germinants, seedlings, saplings, young adults, mature adults and senescent adults respectively. It was not possible to display the sensitivity indices for over 850 parameter alterations. Substrate type starting proportions have been altered in combination and are both displayed in the Tables. The altered and percentage change values relate only to the first nominal value. The amount by which the second nominal parameter decreases depends on the amount by which the first increases, so that all substrate starting proportions do not constitute more or less than 100% of the plot area.

The first notable result from the sensitivity analyses is the general sensitivity of each functional size class of *B. salicina* (Table 7.7). The mean and range of all the sensitivity indices clearly indicate that the smaller size classes are more sensitive than the larger size classes. The frequency of occurrence of S-values shows germinants, seedlings and saplings to most frequently have values which are markedly higher than adults.

Within the smaller size classes, germinants and seedlings are more sensitive than saplings, while within the three adult size classes, mature adults are least sensitive in the model and senescent adults most sensitive. All S-values for the three adult groups are below 2, and almost all below 1. Senescent adults have higher S-values more frequently than young and mature adults.

Table 7.7 The general sensitivity of each functional size class of *Breonadia salicina*.

Biological Class	Sensitivity Index		Frequency of Occurrence of Sensitivity Index			
	Mean	Range	>=1	>=2	>=10	>=1000
Germinants	808175	439102903	11	10	6	6
Seedlings	520554	242455000	11	8	8	4
Saplings	24926	7093575	8	7	4	4
Young Adults	0.05	1.21	1	0	0	0
Mature Adults	0.05	1	1	0	0	0
Senescent Adults	0.07	1.762	7	0	0	0

7.4.2.1 Germinants

Assessment of the sensitivity of germinants (Table 7.1) shows that they are most sensitive to parameter changes of hydrological states and events, followed by substrate proportions, followed by rainfall totals in the wet season, followed by fecundity levels with no hydrological events, density dependence of survival, and finally the area of the site being modeled.

The first two parameter changes shown in Table 7.1 increase the range of discharge which is classified as a large flood. The magnitude of the change has two important consequences. Firstly, large floods will become more frequent and secondly, the amount of discharge that is required before the model registers a catastrophic flood is increased. Specifically, with the given parameter changes in conjunction with the hydrological scenario we used for sensitivity analysis, a catastrophic flood was effectively eliminated. The sensitivity of germinants to the elimination of catastrophic floods was due to the extreme affect they have on survival.

Germinants were also highly sensitive to the event weighting of catastrophic floods. In the rules, this parameter affects the fecundity of *B. salicina* and ordinarily has a value of 0, which means that when a catastrophic flood occurs, fecundity is set to 0 on active, seasonal and ephemeral geomorphological features. By introducing a value (the altered parameter) the model recognizes the presence of incoming germinants despite a catastrophic flood. It is only their presence on active and seasonal features that markedly modify the model response.

Table 7.1 The 50 most sensitive parameters for Germinants, showing the sensitivity index and the associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER			**VALUE**			**INDEX**
Description			Nominal	Altered	% change	Germinants
HydroStates	Large Floods		2000	3000	1.50	439102903.260
HydroStates	Large Floods		2000	4000	2.00	219551451.630
EventWeight Cat Flood	active		0	0.01	value	2561.272
EventWeight Cat Flood	active		0	0.1	value	2475.707
EventWeight Cat Flood	seasonal		0	0.01	value	1642.029
EventWeight Cat Flood	seasonal		0	0.1	value	1597.983
HydroStates	Vsmall Flood		300	450	1.50	3.817
HydroStates	Vsmall Flood		300	500	1.67	2.863
HydroStates	Small Floods		500	750	1.50	2.581
HydroStates	Small Floods		500	1000	2.00	2.264
HydroStates	Small Floods		500	300	0.60	1.178
SEASONALrock^gravel>		0.76	0.01	0.77	1.01	0.967
SEASONALlfa^rock>		0.04	0.76	0.08	2.00	0.879
SEASONALmud^rock>		0.04	0.76	0.08	2.00	0.879
SEASONALgravel^rock>		0.01	0.76	0.02	2.00	0.847
SEASONALrock^lfa>		0.76	0.04	0.8	1.05	0.821
SEASONALrock^mud>		0.76	0.04	0.8	1.05	0.821
HydroStates	Vsmall Flood		300	120	0.40	0.786
SEASONALrock^lca>		0.76	0.06	0.82	1.08	0.774
ACTIVElca^rock>		0.04	0.56	0.08	2.00	0.770
ACTIVElfa^rock>		0.04	0.65	0.08	2.00	0.770
ACTIVEmud^rock>		0.04	0.56	0.08	2.00	0.770
HydroStates	*Vsmall Flood*		*300*	*150*	*0.50*	*0.764*
longevity	saplings (4)		2	1	0.25	0.763
ACTIVErock^lca>		0.56	0.04	0.6	1.07	0.757
ACTIVErock^lfa>		0.56	0.04	0.6	1.07	0.757
ACTIVErock^mud>		0.56	0.04	0.6	1.07	0.757
SEASONALrock^firm>		0.76	0.09	0.85	1.12	0.723
ACTIVElca^firm>		0.04	0.32	0.08	2.00	0.720
ACTIVElfa^firm>		0.04	0.32	0.08	2.00	0.720
ACTIVEmud^firm>		0.04	0.32	0.08	2.00	0.720
ACTIVEfirm^lca>		0.32	0.04	0.36	1.13	0.717
ACTIVEfirm^lfa>		0.32	0.04	0.36	1.13	0.717
ACTIVEfirm^mud>		0.32	0.04	0.36	1.13	0.717
Rainfalltotals	wet		550	300	0.55	0.697
SEASONALlca^rock>		0.06	0.76	0.12	2.00	0.673
HydroStates	Large Floods		2000	500	0.25	0.578
Rainfalltotals	dry		300	450	1.50	0.512
SEASONALfirm^rock>		0.09	0.76	0.18	2.00	0.481
SEASONALfirm^gravel>		0.09	0.01	0.1	1.11	0.478
Fecundity NoEvent	seasonal		3071	768	0.25	0.455
DensDepSurvival	young adults (5)		0.08	0.02	0.25	0.454
Plot Area	hectares		6	1.5	0.25	0.441
Fecundity NoEvent	seasonal		3071	1536	0.50	0.438
Rainfalltotals	dry		300	550	1.83	0.435
DensDepSurvival	saplings (4)		0.09	0.0225	0.25	0.418
HydroStates	Base Flows		5	2.5	0.50	0.401
SEASONALlca^gravel>		0.06	0.01	0.07	1.17	0.390
ACTIVErock^firm>		0.56	0.32	0.88	1.57	0.389
Fecundity NoEvent	seasonal		3071	4607	1.50	0.387

where:

Cat =	Catastrophic	dry =	dry rainfall year
^ =	an increase	wet =	wet rainfall year
> =	a decrease	germ =	germinants
lfa =	loose fine alluvium	seedl =	seedlings
lca =	loose coarse alluvium	Dry =	dry season
firm =	firm alluvium	Wet =	wet season
() =	contains size class number		

Sensitivity of germinants to very small and small floods (Table 7.1) is essentially a sensitivity to small floods. This is because the frequency of small floods either decreases as the range of very small floods is increased, increases as the range of small floods is increased, or is eliminated when the upper range of very small and small floods are made equal. Since small floods affect the response of germinants via their influence on germinant survival, the model is displaying sensitivity to germinant survival influenced by small floods.

The sensitivity of germinants to certain changes in substrate starting proportions relates to seasonal and active exposed bedrock dynamics; Either an increase (rock^) or a decrease (rock>) in exposed bedrock (Table 7.1). Sensitivity indices are also high for increases and decreases in the proportion of firm alluvium on active geomorphological features. The reason for this sensitivity to changes in exposed bedrock and firm alluvium is because the survival probabilities of *B. salicina* germinants is higher on active and seasonal exposed bedrock (0.825) and active firm alluvium (0.033) than all other substrate types (0.0001).

7.4.2.2 Seedlings

Seedlings are most sensitive to changes in hydrological states (large floods), followed by seedling longevity, followed by hydrological event weighting for catastrophic floods, followed by density dependence relating to germinant survival (Table 7.2). It is also notable that many of the parameters to which seedlings are sensitive involve changes to germinants, i.e. altered parameters at the germinant level influence seedlings markedly.

The discussion for sensitivity of seedlings to changes in large floods is the same as sensitivity of germinants to large floods (section 7.4.2.1). Clearly seedlings are highly sensitive to changes in their own longevity, and in particular to an increase by a factor of 2. It is not clear why this sensitivity is so acute, but it may be related to the vulnerability of the seedling stage.

Seedling sensitivity to density dependence on the survival of germinants, is also high. Seedlings are however, more sensitive to reductions in density dependence effects, which result in potentially more germinants becoming seedlings, than to increases in density dependence effects, which constrains the numbers of germinants that potentially become seedlings.

Table 7.2 The 50 most sensitive parameters for Seedlings, showing the sensitivity index and the associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER		**VALUE**			**INDEX**
Description		Nominal	Altered	% change	Seedlings
HydroStates	Large Floods	2000	3000	1.50	242455000.033
HydroStates	Large Floods	2000	4000	2.00	121227500.017
longevity	seedlings (2)	1	2	2.00	36682468.102
longevity	seedlings (3)	1	2	2.00	23885822.615
EventWeight Cat Flood	active	0	0.01	value	464.332
EventWeight Cat Flood	seasonal	0	0.01	value	351.855
EventWeight Cat Flood	active	0	0.1	value	117.978
EventWeight Cat Flood	seasonal	0	0.1	value	91.053
DensDepSurvival	germinants (1)	0.0006	0.00015	0.25	1.694
HydroStates	Vsmall Flood	300	450	1.50	1.099
DensDepSurvival	germinants (1)	0.0006	0.0003	0.50	1.041
HydroStates	Vsmall Flood	300	500	1.67	0.824
HydroStates	Vsmall Flood	300	120	0.40	0.641
HydroStates	Vsmall Flood	300	150	0.50	0.582
survivalRock Seasonal	germinants (1)	0.825	0.20625	0.25	0.482
HydroStates	Small Floods	500	300	0.60	0.445
DensDepSurvival	germinants (1)	0.0006	0.0009	1.50	0.443
survivalRock Seasonal	germinants (1)	0.825	1	1.21	0.431
RainPeriodsFrequGerm	Absent Dry	3	4.5	1.50	0.426
longevity	germinants (1)	1	2	2.00	0.414
HydroStates	Large Floods	2000	500	0.25	0.410
survivalRock Active	germinants (1)	0.825	0.20625	0.25	0.351
DensDepSurvival	germinants (1)	0.0006	0.0012	2.00	0.351
survivalRock Active	germinants (1)	0.825	1	1.21	0.340
RainPeriodsFrequGerm	Absent Dry	3	1.5	0.50	0.297
RainPeriodsFrequGerm	Absent Wet	2	3	1.50	0.272
RainPeriodsFrequGerm	Absent Dry	3	0.75	0.25	0.259
SEASONALfirm^gravel>	0.09	0.01	0.1	1.11	0.243
RainPeriodsFrequGerm	Absent Wet	2	1	0.50	0.237
DensDepSurvival	seedlings (2)	0.001	0.00025	0.25	0.230
RainPeriodsFrequGerm	Absent Dry	3	6	2.00	0.228
SEASONALlca^gravel>	0.06	0.01	0.07	1.17	0.228
ACTIVErock^firm>	0.56	0.32	0.88	1.57	0.220
SEASONALlfa^gravel>	0.04	0.01	0.05	1.25	0.214
SEASONALmud^gravel>	0.04	0.01	0.05	1.25	0.214
HydroStates	Small Floods	500	1000	2.00	0.203
SEASONALfirm^rock>	0.09	0.76	0.18	2.00	0.201
HydroStates	Small Floods	500	750	1.50	0.199
SEASONALgravel^firm>	0.01	0.09	0.02	2.00	0.182
SEASONALlca^rock>	0.06	0.76	0.12	2.00	0.169
ACTIVEfirm^rock>	0.32	0.56	0.64	2.00	0.168
SEASONALgravel^lca>	0.01	0.06	0.02	2.00	0.164
Rainfalltotals	wet	550	300	0.55	0.161
RainPeriodsFrequGerm	Present wet	3	0.75	0.25	0.161
RainPeriodsFrequGerm	Absent Wet	2	0.5	0.25	0.158
RainPeriodsFrequGerm	Absent Wet	2	4	2.00	0.155
SEASONALgravel^lfa>	0.01	0.04	0.02	2.00	0.148
SEASONALgravel^mud>	0.01	0.04	0.02	2.00	0.148
Plot Area	hectares	6	1.5	0.25	0.145
Fecundity NoEvent	seasonal	3071	767.75	0.25	0.144

where:

Cat =	Catastrophic	dry =	dry rainfall year
^ =	an increase	wet =	wet rainfall year
> =	a decrease	germ =	germinants
lfa =	loose fine alluvium	seedl =	seedlings
lca =	loose coarse alluvium	Dry =	dry season
firm =	firm alluvium	Wet =	wet season
() =	contains size class number		

Sensitive to changes in very small and small floods (Table 7.2) is a sensitivity to small floods. The nature of the parameter changes means that the frequency of small floods either decreases as the range of very small floods is increased, increases as the range of small floods is increased, or is eliminated when the upper range of very small and small floods are made equal. Small floods affect the response of seedlings via their influence on germinant and seedling survival.

Seedlings are also sensitive to changes in the survival probabilities of germinants on seasonal and active exposed bedrock, the effect on germinants of the frequency of occurrence of wet and dry periods in a rainfall year, and changes in substrate starting proportions involving either increases or decreases of both seasonal and active gravel and exposed bedrock.

7.4.2.3 Saplings

Saplings are most sensitive to changes in hydrological states of large and catastrophic floods, followed by the catastrophic flood factor, followed by hydrological states of small and very small floods, followed by the longevity of seedlings and saplings (Table 7.3).

Elimination of catastrophic floods affects saplings in the same way as it does germinants and seedlings. The catastrophic flood factor is used to calculate the probability of staying and survival for each of the 14 size classes in years that experience catastrophic floods. The extreme influence of reducing the catastrophic flood factor on saplings is due to survival probabilities increasing from zero to 0.468 when the effect of the catastrophic flood is reduced in that year. The resulting effect is that saplings survive better and become young adults quicker.

Altered frequency of small floods also affects saplings in the same way as germinants and seedlings. Saplings are also highly sensitive to doubling the longevity of first year seedlings (size class 2), and less so to changes in their own longevity (size class 4), increases in second year seedling longevity (size class 3), and increases in germinant longevity (size class 1).

Other parameter changes to which seedlings are sensitive include a decrease in density dependence on the survival of germinants, seedlings and saplings, a decrease in the starting proportions of active exposed bedrock and seasonal exposed bedrock and gravel, survival of germinants and seedlings on seasonal and active exposed bedrock, and rainfall periodicity.

Table 7.3 The 50 most sensitive parameters for Saplings, showing the sensitivity index and the associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER		VALUE			INDEX
Description		Nominal	Altered	% change	Saplings
HydroStates	Large Floods	2000	3000	1.50	7093574.687
Cat Flood Factor		4	2	0.50	4944919.325
Cat Flood Factor		4	1	0.25	4729049.444
HydroStates	Large Floods	2000	4000	2.00	3546787.343
HydroStates	Small Floods	500	750	1.50	7.370
longevity	seedlings (2)	1	2	2.00	6.463
HydroStates	Small Floods	500	1000	2.00	4.795
HydroStates	Vsmall Flood	300	450	1.50	1.033
HydroStates	Small Floods	500	300	0.60	0.981
HydroStates	Vsmall Flood	300	500	1.67	0.775
HydroStates	Vsmall Flood	300	120	0.40	0.620
longevity	saplings (4)	2	0.5	0.25	0.592
HydroStates	Vsmall Flood	300	150	0.50	0.571
HydroStates	Large Floods	2000	500	0.25	0.523
DensDepSurvival	saplings (4)	0.09	0.0225	0.25	0.484
ACTIVEfirm^rock>	0.32	0.56	0.64	2.00	0.434
ACTIVElca^rock>	0.04	0.56	0.08	2.00	0.417
ACTIVElfa^rock>	0.04	0.65	0.08	2.00	0.417
ACTIVEmud^rock>	0.04	0.56	0.08	2.00	0.417
SEASONALfirm^rock>	0.09	0.76	0.18	2.00	0.411
DensDepSurvival	germinants (1)	0.0006	0.00015	0.25	0.392
SEASONALlca^rock>	0.06	0.76	0.12	2.00	0.361
survivalRock Seasonal	seedlings (3)	0.915	0.22875	0.25	0.345
survivalRock Seasonal	seedlings (3)	0.915	1	1.09	0.335
DensDepSurvival	germinants (1)	0.0006	0.0003	0.50	0.326
DensDepSurvival	seedlings (3)	0.001	0.00025	0.25	0.324
SEASONALfirm^gravel>	0.09	0.01	0.1	1.11	0.314
SEASONALlfa^rock>	0.04	0.76	0.08	2.00	0.313
SEASONALmud^rock>	0.04	0.76	0.08	2.00	0.313
RainPeriodsFrequSeedl	Absent Dry	3	1.5	0.50	0.312
survivalRock Seasonal	germinants (1)	0.825	0.20625	0.25	0.304
RainPeriodsFrequSeedl	Absent Dry	3	4.5	1.50	0.291
longevity	saplings (4)	2	3	1.50	0.282
longevity	seedlings (3)	1	2	2.00	0.277
SEASONALlca^gravel>	0.06	0.01	0.07	1.17	0.275
survivalRock Active	germinants (1)	0.825	0.20625	0.25	0.259
RainPeriodsFrequSeedl	Absent Dry	3	0.75	0.25	0.256
DensDepSurvival	seedlings (2)	0.001	0.00025	0.25	0.248
SEASONALlfa^gravel>	0.04	0.01	0.05	1.25	0.239
SEASONALmud^gravel>	0.04	0.01	0.05	1.25	0.239
survivalRock Active	seedlings (3)	0.915	1	1.09	0.234
survivalRock Active	seedlings (3)	0.915	0.22875	0.25	0.233
longevity	germinants (1)	1	2	2.00	0.226
SEASONALgravel^firm>	0.01	0.09	0.02	2.00	0.226
RainPeriodsFrequSeedl	Absent Wet	3	0.75	0.25	0.213
longevity	saplings (4)	2	4	2.00	0.212
DensDepSurvival	germinants (1)	0.0006	0.0009	1.50	0.212
survivalRock Active	germinants (1)	0.825	1	1.21	0.207
ACTIVErock^lca>	0.56	0.04	0.6	1.07	0.205
ACTIVErock^lfa>	0.56	0.04	0.6	1.07	0.205

where:

Cat = Catastrophic
^ = an increase
> = a decrease
lfa = loose fine alluvium
lca = loose coarse alluvium
firm = firm alluvium
() = contains size class number

dry = dry rainfall year
wet = wet rainfall year
germ = germinants
seedl = seedlings
Dry = dry season
Wet = wet season

7.4.2.4 Young Adults

Young adults (size class 5) are most sensitive to a reduction in sapling longevity, but are also sensitive to a reduction in their own longevity, and extended longevities of saplings (Table 7.4). Increases and decreases in active firm alluvium and exposed bedrock, and seasonal exposed bedrock, firm alluvium and gravel starting proportions also result in high sensitivity indices for young adults. This is likely to be related to survival probability of germinants and seedlings being highest on bedrock, followed by firm alluvium.

The effect of hydrological states on young adult sensitivity is similar to smaller size classes, with emphasis on the elimination of small and large floods, and the increase in frequency of small floods. Reduction in density dependence on the survival of saplings and young adults also elicits a sensitive response by young adults.

7.4.2.5 Mature Adults

Mature adults (size classes 6 to 10) are sensitive to the same four parameter changes as young adults, namely, longevity, substrate starting proportions, hydrological states and the effect of density dependence on survival (Table 7.5).

Sensitivity of mature adults is high to reductions in young adult longevity, increases in young adult longevity, and reduction in sapling longevity. Important substrate starting proportion changes are increases and decreases to active and seasonal exposed bedrock firstly, and firm alluvium secondly. Mature adults are also sensitive to the elimination of small and large floods and the increase in frequency of small floods, reductions in the effect of density dependence on the survival of young and mature adults, and changes in survival probabilities of young and mature adults growing on active exposed bedrock and firm alluvium, and seasonal exposed bedrock.

Table 7.4 The 50 most sensitive parameters for Young Adults, showing the sensitivity index and associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER			VALUE			INDEX
Description			Nominal	Altered	% change	Young Adults
longevity	saplings (4)		2	0.5	0.25	1.210
SEASONALrock^gravel>		0.76	0.01	0.77	1.01	0.943
ACTIVEfirm^lca>		0.32	0.04	0.36	1.13	0.922
ACTIVEfirm^lfa>		0.32	0.04	0.36	1.13	0.922
ACTIVEfirm^mud>		0.32	0.04	0.36	1.13	0.922
ACTIVErock^lca>		0.56	0.04	0.6	1.07	0.880
ACTIVErock^lfa>		0.56	0.04	0.6	1.07	0.880
ACTIVErock^mud>		0.56	0.04	0.6	1.07	0.880
SEASONALrock^lfa>		0.76	0.04	0.8	1.05	0.784
SEASONALrock^mud>		0.76	0.04	0.8	1.05	0.784
HydroStates	Small Floods		500	300	0.60	0.782
SEASONALgravel^rock>		0.01	0.76	0.02	2.00	0.776
SEASONALrock^lca>		0.76	0.06	0.82	1.08	0.741
DensDepSurvival	saplings (4)		0.09	0.0225	0.25	0.720
SEASONALrock^firm>		0.76	0.09	0.85	1.12	0.699
longevity	young adults (5)		3	0.75	0.25	0.639
SEASONALfirm^gravel>		0.09	0.01	0.1	1.11	0.548
longevity	saplings (4)		2	3	1.50	0.524
ACTIVElca^firm>		0.04	0.32	0.08	2.00	0.511
ACTIVElfa^firm>		0.04	0.32	0.08	2.00	0.511
ACTIVEmud^firm>		0.04	0.32	0.08	2.00	0.511
HydroStates	Small Floods		500	750	1.50	0.475
DensDepSurvival	young adults (5)		0.08	0.02	0.25	0.468
SEASONALlca^gravel>		0.06	0.01	0.07	1.17	0.457
SEASONALlfa^rock>		0.04	0.76	0.08	2.00	0.452
SEASONALmud^rock>		0.04	0.76	0.08	2.00	0.452
ACTIVElca^rock>		0.04	0.56	0.08	2.00	0.448
ACTIVElfa^rock>		0.04	0.65	0.08	2.00	0.448
ACTIVEmud^rock>		0.04	0.56	0.08	2.00	0.448
HydroStates	Vsmall Flood		300	120	0.40	0.447
HydroStates	Large Floods		2000	500	0.25	0.441
longevity	young adults (5)		3	1.5	0.50	0.437
longevity	saplings (4)		2	4	2.00	0.412
HydroStates	Vsmall Flood		300	150	0.50	0.410
SEASONALfirm^lfa>		0.09	0.04	0.13	1.44	0.382
SEASONALfirm^mud>		0.09	0.04	0.13	1.44	0.382
ACTIVErock^firm>		0.56	0.32	0.88	1.57	0.378
SEASONALgravel^firm>		0.01	0.09	0.02	2.00	0.377
SEASONALlfa^gravel>		0.04	0.01	0.05	1.25	0.372
SEASONALmud^gravel>		0.04	0.01	0.05	1.25	0.372
SEASONALfirm^lca>		0.09	0.06	0.15	1.67	0.335
SEASONALlca^rock>		0.06	0.76	0.12	2.00	0.333
ACTIVElca^lfa>		0.04	0.04	0.08	2.00	0.318
ACTIVElca^mud>		0.04	0.04	0.08	2.00	0.318
ACTIVElfa^lca>		0.04	0.04	0.08	2.00	0.318
ACTIVElfa^mud>		0.04	0.04	0.08	2.00	0.318
ACTIVEmud^LCA>		0.04	0.04	0.08	2.00	0.318
ACTIVEmud^LFA>		0.04	0.04	0.08	2.00	0.318
HydroStates	Small Floods		500	1000	2.00	0.316
SEASONALlca^lfa>		0.06	0.04	0.1	1.67	0.305

where:

Cat = Catastrophic
^ = an increase
> = a decrease
lfa = loose fine alluvium
lca = loose coarse alluvium
firm = firm alluvium
() = contains size class number

dry = dry rainfall year
wet = wet rainfall year
germ = germinants
seedl = seedlings
Dry = dry season
Wet = wet season

Table 7.5 The 50 most sensitive parameters for Mature Adults, showing the sensitivity index and associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER		VALUE			INDEX
Description		Nominal	Altered	% change	Mature Adults
longevity	young adults (5)	3	0.75	0.25	1.000
ACTIVErock^lca>	0.56	0.04	0.6	1.07	0.922
ACTIVErock^lfa>	0.56	0.04	0.6	1.07	0.922
ACTIVErock^mud>	0.56	0.04	0.6	1.07	0.922
SEASONALrock^gravel>	0.76	0.01	0.77	1.01	0.848
ACTIVEfirm^lca>	0.32	0.04	0.36	1.13	0.834
ACTIVEfirm^lfa>	0.32	0.04	0.36	1.13	0.834
ACTIVEfirm^mud>	0.32	0.04	0.36	1.13	0.834
longevity	young adults (5)	3	1.5	0.50	0.800
SEASONALgravel^rock>	0.01	0.76	0.02	2.00	0.762
SEASONALrock^lfa>	0.76	0.04	0.8	1.05	0.724
SEASONALrock^mud>	0.76	0.04	0.8	1.05	0.724
HydroStates	Small Floods	500	300	0.60	0.687
SEASONALrock^lca>	0.76	0.06	0.82	1.08	0.677
ACTIVElca^rock>	0.04	0.56	0.08	2.00	0.646
ACTIVElfa^rock>	0.04	0.65	0.08	2.00	0.646
ACTIVEmud^rock>	0.04	0.56	0.08	2.00	0.646
SEASONALrock^firm>	0.76	0.09	0.85	1.12	0.626
SEASONALlfa^rock>	0.04	0.76	0.08	2.00	0.548
SEASONALmud^rock>	0.04	0.76	0.08	2.00	0.548
ACTIVElca^firm>	0.04	0.32	0.08	2.00	0.531
ACTIVElfa^firm>	0.04	0.32	0.08	2.00	0.531
ACTIVEmud^firm>	0.04	0.32	0.08	2.00	0.531
SEASONALlca^rock>	0.06	0.76	0.12	2.00	0.459
DensDepSurvival	young adults (5)	0.08	0.02	0.25	0.454
longevity	young adults (5)	3	4.5	1.50	0.449
ACTIVErock^firm>	0.56	0.32	0.88	1.57	0.431
longevity	saplings (4)	2	0.5	0.25	0.428
survivalRock Active	mature adults (6)	0.967	1	1.03	0.410
survivalRock Seasonal	mature adults (6)	0.984	1	1.02	0.399
Plot Area	hectares	6	1.5	0.25	0.396
SEASONALfirm^gravel>	0.09	0.01	0.1	1.11	0.391
HydroStates	Large Floods	2000	500	0.25	0.383
longevity	young adults (5)	3	6	2.00	0.376
SEASONALfirm^rock>	0.09	0.76	0.18	2.00	0.355
survivalRock Active	mature adults (7)	0.967	1	1.03	0.342
survivalRock Active	mature adults (6)	0.967	0.24175	0.25	0.321
SEASONALlca^gravel>	0.06	0.01	0.07	1.17	0.316
DensDepSurvival	mature adults (6)	0.05	0.0125	0.25	0.314
HydroStates	Vsmall Flood	300	120	0.40	0.300
SEASONALfirm^lfa>	0.09	0.04	0.13	1.44	0.294
SEASONALfirm^mud>	0.09	0.04	0.13	1.44	0.294
survivalRock Seasonal	mature adults (6)	0.984	0.246	0.25	0.293
SEASONALgravel^firm>	0.01	0.09	0.02	2.00	0.279
HydroStates	Vsmall Flood	300	150	0.50	0.272
survivalFirmActive	mature adults (6)	0.967	1	1.03	0.268
survivalRock Active	young adults (5)	0.946	0.2365	0.25	0.268
survivalRock Seasonal	young adults (5)	0.974	0.2435	0.25	0.263
SEASONALfirm^lca>	0.09	0.06	0.15	1.67	0.262
ACTIVElca^lfa>	0.04	0.04	0.08	2.00	0.261

where:

Cat =	Catastrophic	dry =	dry rainfall year
^ =	an increase	wet =	wet rainfall year
> =	a decrease	germ =	germinants
lfa =	loose fine alluvium	seedl =	seedlings
lca =	loose coarse alluvium	Dry =	dry season
firm =	firm alluvium	Wet =	wet season
() =	contains size class number		

7.4.2.6 Senescent Adults

Senescent adults (size classes 11 to 14) are most sensitive to a reduction by a factor of 0.25 of plot area. Plot area reduction results in an increased density for all size classes (Table 7.6). Senescent adults did not however, respond to changes in their own density dependence, suggesting that estimation of their density dependence is too low. This, was also highlighted in the scenario outputs of the model (section 7.3) .

Changes to mature and senescent adults survival probability on active exposed bedrock and firm alluvium, and increases to mature and senescent adults survival probability on seasonal are also highly influential on senescent adults.

Other important parameter changes include the decrease, elimination or increase of small floods, the decrease or increase of base and intermediate flows which are used to define drought periods, altered longevity of mature adults, changes to active exposed bedrock and firm alluvium starting proportions, and a decrease in the small flood factor. The small flood factor defines the extent of influence of a small flood relative to a large flood.

7.4.3 Significance of results of sensitivity analyses

Haefner (1996) discusses four general uses of sensitivity analyses which are briefly outlined because they have guided our recommendations for research and monitoring (chapter 8):

- Validation: results from sensitivity analyses help to validate the model in 2 ways. Firstly, we do not generally expect extreme responses to small parameter changes. If this is not the case we can assume that there are no extremely unrealistic errors in the model mechanism. If this is the case however, then we need to investigate the validity of the response. Secondly, if we are not confident in the estimation of a parameter and the model is sensitive to changes in that parameter, then we can not be confident in the model output. If however, the model is not sensitive to changes in that parameter, then we can assume that our lack of confidence in parameter estimation will not reduce our confidence in the model output. Extreme sensitivity as outlined in the results above, were used to further validate the *Breonadia* model, where explanations for sensitivity were inadequate.
- Research design: models will be more sensitive to changes in some parameters than others. Research should be prioritised so that the greatest research effort focusses on obtaining

confident estimates of the parameters to which the model is most sensitive. We used results from the sensitivity analyses to suggest research and monitoring for auditing the TPC and refining the *Breonadia* model. Details are discussed in chapter 8.

- System control: in order to manage a system, we need to exert at least some control on that system. Controlling the system means that managers manipulate system variables and parameters to achieve the desired output. If the system is insensitive to a variable or parameter, then its manipulation will not change the way the system behaves. Sensitivity analyses are useful therefore to indicate which of the variable or parameters have potential as controllers, i.e. which will be the most sensible for managers to manipulate. Results indicate that managers should focus on hydrological flows (states), substrate proportional changes (particularly exposed bedrock, firm alluvium and gravel), and germinants seedlings and saplings of the *B. salicina* population.

A concise summary of the sensitivity analyses is given in Table 8.1.

Table 7.6 The 50 most sensitive parameters for Senescent Adults, showing the sensitivity index and associated % change for each nominal parameter. Altered parameter values are also indicated.

PARAMETER			VALUE			INDEX
Description			Nominal	Altered	% change	Senescent Adults
Plot Area	hectares		6	1.5	0.25	1.762
survivalRock Active	mature adults (10)		0.982	1	1.02	1.513
survivalRock Active	senscent adults (11)		0.955	1	1.05	1.512
survivalRock Seasonal	senscent adults (11)		0.998	1	1.00	1.081
HydroStates	Vsmall Flood		300	450	1.50	1.077
survivalRock Active	mature adults (9)		0.967	1	1.03	1.061
survivalRock Seasonal	mature adults (10)		0.991	1	1.01	1.021
Plot Area	hectares		6	3	0.50	0.966
survivalRock Active	senscent adults (12)		0.999	1	1.00	0.943
longevity	mature adults (10)		7	1.75	0.25	0.891
survivalFirmActive	mature adults (10)		0.982	1	1.02	0.859
survivalFirmActive	senscent adults (11)		0.955	1	1.05	0.824
HydroStates	Vsmall Flood		300	500	1.67	0.808
HydroStates	Vsmall Flood		300	120	0.40	0.806
HydroStates	Vsmall Flood		300	150	0.50	0.777
longevity	mature adults (10)		7	3.5	0.50	0.753
longevity	mature adults (9)		6	1.5	0.25	0.738
survivalRock Active	mature adults (8)		0.967	1	1.03	0.712
HydroStates	Small Floods		500	300	0.60	0.684
longevity	mature adults (9)		6	3	0.50	0.672
ACTIVErock^lca>		0.56	0.04	0.6	1.07	0.653
ACTIVErock^lfa>		0.56	0.04	0.6	1.07	0.653
ACTIVErock^mud>		0.56	0.04	0.6	1.07	0.653
survivalRock Active	senscent adults (13)		0.995	1	1.01	0.652
longevity	mature adults (8)		6	1.5	0.25	0.651
longevity	mature adults (8)		6	3	0.50	0.592
longevity	mature adults (7)		6	1.5	0.25	0.591
smallfloodfactor			0.25	0.0625	0.25	0.561
ACTIVElca^rock>		0.04	0.56	0.08	2.00	0.558
ACTIVElfa^rock>		0.04	0.65	0.08	2.00	0.558
ACTIVEmud^rock>		0.04	0.56	0.08	2.00	0.558
HydroStates	Base Flows		5	2.5	0.50	0.539
ACTIVEfirm^lca>		0.32	0.04	0.36	1.13	0.528
ACTIVEfirm^lfa>		0.32	0.04	0.36	1.13	0.528
ACTIVEfirm^mud>		0.32	0.04	0.36	1.13	0.528
survivalRock Active	mature adults (10)		0.982	0.2455	0.25	0.527
longevity	mature adults (7)		6	3	0.50	0.525
survivalRock Active	senscent adults (14)		0.985	1	1.02	0.508
survivalRock Active	senscent adults (11)		0.955	0.23875	0.25	0.508
longevity	mature adults (10)		7	10.5	1.50	0.460
HydroStates	Base Flows		5	1.25	0.25	0.445
survivalRock Active	mature adults (9)		0.967	0.24175	0.25	0.441
survivalRock Active	mature adults (7)		0.967	1	1.03	0.428
survivalFirmActive	mature adults (10)		0.982	0.2455	0.25	0.418
HydroStates	Base Flows		5	7.5	1.50	0.410
longevity	mature adults (9)		6	9	1.50	0.405
survivalFirmActive	senscent adults (11)		0.955	0.23875	0.25	0.397
ACTIVElca^firm>		0.04	0.32	0.08	2.00	0.392
ACTIVElfa^firm>		0.04	0.32	0.08	2.00	0.392
ACTIVEmud^firm>		0.04	0.32	0.08	2.00	0.392

where:

Cat = Catastrophic
^ = an increase
> = a decrease
lfa = loose fine alluvium
lca = loose coarse alluvium
firm = firm alluvium
() = contains size class number

dry = dry rainfall year
wet = wet rainfall year
germ = germinants
seedl = seedlings
Dry = dry season
Wet = wet season

Chapter 8

MONITORING TO MEET MANAGEMENT GOALS

Monitoring is dealt with under four sections; (1) data required to audit the TPC, (2) data required for refinement of the *Breonadia* model, (3) a recommended monitoring programme that outlines the type of data to be collected, where the data are to be collected, how the data are collected, and when to sample, and (4) use of the monitoring data.

8.1 DATA TO AUDIT THE TPC

Since the "loss of bedrock influence TPC" involves the structure of non-germinant *B. salicina* population, detailed population data must be collected to audit the TPC. The three parameters of the TPC (r^2, x-coefficient, and constant) can be determined form the population densities of each non germinant functional size class. The collection of data and evaluation of the TPC need to take place at regular five years intervals at a number of field sites.

Since evaluation of the TPC also requires an understanding of associated hydrological events (see section 7.2), it is also necessary to record daily discharge ($m^3.s^{-1}$) from the closest available gauging station.

Data collected during monitoring exercises can be used as a direct audit of the TPC. However, management the runs the risk of becoming reactive to system change because awareness is only created after the TPC has been reached or passed. An important purpose of the model is to provide the potential for "predictive monitoring", whereby monitoring data can be fed into the model to predict the likelihood of reaching the TPC, given future management and environmental scenarios (see Figure 7.7).

8.2 MONITORING FOR REFINEMENT OF THE *BREONADIA* MODEL

An aim of monitoring, is to obtain field data to audit the TPC, which can be used in further refinement of the model to improve confidence in TPC parameter and overall predictive capability.

Refinement of the *Breonadia* model can be achieved through (1) testing the model output, (2) addressing inherent assumptions made in the model, (3) improving variable and parameter estimation in the model, and (4) upgrading the substrate type-hydrology link.

8.2.1 Monitoring to test the model

Data against which the *Breonadia* model can be tested, are a minimum requirement of monitoring. If resources for monitoring are limited, these data, as well as data required to audit the TPC, should be the last to be eliminated from a monitoring programme.

Monitoring to test the *Breonadia* model needs to record change in the population structure in response to environmental variables used in the model. The type of data obtained at each field site, should therefore, match the model input and output data:

1. Hydrological data for the year; daily discharge, collected at the closest possible gauging station.
2. Rainfall; daily rainfall, collected at the closest possible site.
3. Proportion of different substrate types.
4. Population densities of each functional size class.

Collection of data to test the model must take place both before and following the hydrological event being tested. The details of how, when and where these data should be collected are presented in section 8.3

8.2.2 Data to address inherent assumptions

A number of important assumptions are made within the model and need to be addressed through further research or monitoring:

1. High flows (20-120 $m^3.s^{-1}$) and very small floods (120-300 $m^3.s^{-1}$) have no influence in the model, while extreme low flows (0-1 $m^3.s^{-1}$) to intermediate flows (5-20 $m^3.s^{-1}$) are only used to determine the occurrence of a drought event. Data needs to be collected on the response (fecundity and survival) of the different size classes (especially germinants to saplings) to these lower hydrological states. Inclusion of these hydrological states as events in the model will greatly improve the accuracy of the model output.
2. Growth rates are independent of substrate type and inundation frequency. Measurement of growth rates of different size classes on different substrate types and flooding frequency levels are required to address this assumption.
3. Drought and rainfall do not influence growth rate. Growth rates of the different size classes need to be measured under no event, drought, and wet and dry rainfall years.
4. Damage caused by flooding reduces growth rate of an individual. Growth rates need to be measured before and after flooding events.
5. Size classes cannot skip a size class (e.g germinants to saplings). Growth rates of individuals need to be measured to determine whether size classes are ever skipped during a growing year.
6. Density dependence is independent of substrate type and inundation frequency. The self regulatory effect of density dependence on the different substrate types needs to be determined.
7. All adult size classes have the same density dependence affecting their survival. Differences in density dependence need to be determined for the range of adult size classes.

8. Fecundity is independent of substrate type. The number of germinants per adult needs to be determined on the different substrate types.

9. All adult size classes have the same density dependence affecting their fecundity. The effect of density dependence on fecundity would need to be compared between different adult size classes.

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). The influence of more than one hydrological event in a year on the *B. salicina* population would need to be measured.

11. Herbivory does not influence the *B. salicina* population. Exclosure plots would need to be set up to determine the influence of herbivory.

12. Equal densities of the *B. salicina* population on different substrate types is assumed in the calculation of the vector matrix. Densities on different substrate types need to be determined and built into the calculation of the vector matrix.

The developer, and not the user, of the model would need to correct the assumptions as new rules would need to be developed and coded.

8.2.3 Data to improve parameter estimation

The sensitivity analyses (section 7.4) highlighted a number of variables and parameters that the model was sensitive to (Table 8.1). Many are estimates based on either poor data or an intuitive understanding of the species and should receive priority in improving the model.

8.2.4 Data to improve the substrate type-hydrology link

The current best estimate of change in substrate type is based on the substrate type - hydrology link which was derived form a limited understanding of geomorphological response to flow. A geomorphology model which provides better predictions of change in substrate type should be developed. However, an interim would be to use empirical evidence from a monitoring program of change in substrate type proportion in response to the different hydrological events .

Table 8.1 Summary of the sensitivity analyses with ticks indicating sensitivity.

	Germinants	Seedlings	Saplings	Young Adults	Mature Adults	Senescent Adults
Catastrophic floods	✓	✓	✓			
Large Floods				✓	✓	
Small Floods	✓	✓	✓	✓	✓	✓
Drought						✓
Event Weight	✓Cat Flood	✓Cat flood				
Catastrophic Flood Factor			✓			
Bedrock	✓	✓	✓	✓	✓	✓
Firm Alluvium	✓			✓	✓	✓
Gravel		✓	✓	✓		
Growth Rates		✓ of seedling	✓ of seedlings & saplings	✓ sapling & Yadults	✓ sapling & Yadults	✓MAdults
Rainfall Periodicity	✓	✓				
Density Dependence		✓germinants	✓ germinants, seedlings, saplings	✓ Sapling & Yadults	✓Y & MAdults	✓
Survival probability		✓germinants on rock	✓ germinants, seedlings on rock		✓Y & MAdults on rock	✓M & SAdults on rock & firm Alluvium

8.3 SAMPLING STRATEGY

8.3.1 What to sample

Monitoring to audit the TPC, and test and refine the model will depend entirely on the resources available. We therefore distinguish between data that are essential to monitor, and data that will be useful to monitor.

8.3.1.1 Essential data

Essential data are those required to test the model and audit the TPC:

1. The basal diameter should be recorded for individuals of each of the fourteen size classes on actively, seasonally or ephemerally flooded according (Table 8.1). These data can be used to determine the population structure for input to the model.

Table 8.2 Flooding characteristics of actively, seasonally, and ephemerally flooded geomorphic units (van Coller *et al.*, 1995).

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

2. Proportion of each of the seven substrate types within the sampling area include;
   Mud/silt - very fine clay sized alluvium,
   Loose coarse alluvium - alluvium with loose structure and a particle size of 0.1-1 cm,
   Loose fine alluvium - alluvium with loose structure and a particle size of 0.05- 0.1cm ,
   Firm alluvium - alluvium that has a distinctive form and structure, and often a high proportion of organic matter,
   Gravel - alluvium with a particle size of >1cm (gravel includes cobbles),
   Bedrock - exposed areas of rock that have a fixed position in the riverbed, and
   Parent soil - soil originating from the macro-channel bank.

These substrate data are essential for model testing, and improving the substrate type - hydrology link.

3. Daily discharge ($m^3.s^{-1}$) measured from a gauging station in close proximity to the vegetation monitoring site to test the model and improve the substrate type - hydrology link.

4. Daily rainfall (mm) from a station in within 15km of the vegetation monitoring site.

5. Growth rate - Individuals of all fourteen size classes, on all seven substrate types and inundation frequency levels (active, seasonal and ephemeral), need to be marked and measured annually for growth in basal stem circumference. X,y and z coordinates of each individual , relative to some fixed point, will ensure the same individuals are located each year.

8.3.1.2 Useful data

Useful data will enhance the refinement of the model:

- The influence of very low flows to small floods, and catastrophic floods on survivorship and fecundity. Numbers of individuals in each of the fourteen size classes need to be recorded. These data can also be used to determine the 'combined effects' of hydrological events.
- Density dependence - The influence of density dependence on different substrate types and inundation frequencies can be determined by undertaking a nearest neighbor analysis.
- Fecundity - The number of germinants produced on different substrate types per adult. This can be determined from the number of germinants on a substrate type relative to the number of adults for total sampling area.

The influence of density on fecundity needs to be determined from a relationship of adult size class density and the number of germinants produced per unit area.

- Herbivory - Exclosure plots for germinants, seedlings and saplings to exclude small and large herbivores, as well as insects need to be set up to determine the impact of herbivory on the *B. salicina* population. Survival rates can be compared between open and enclosed plots.

8.3.2 Where to sample

All sampling must be carried out in rapid sections of pool-rapid channel types close to a gauging and weather station. These sections are most responsive to changes in sedimentation.

8.3.3 How to sample

Belt transects perpendicular to the river are the most efficient means for sampling riparian vegetation to account for the changes in flooding levels. The width of each transect should not be greater than the width of the rapid section, since this is the region of bedrock influence. A width of ten meters has been found to be practical. Only the macro-channel floor need be sampled, since *B. salicina* does not grow on the macro-channel bank.

8.3.4 When to sample

Every five years is sufficient to audit the TPC. Monitoring to audit the TPC should also take place in the year following exceedence of the TPC. If a catastrophic flood or a no flow event occurs, then monitoring must only take place five years following the event to allow for sufficient recovery. Likewise, if a large flood occurs, sampling should only take place three years following the event. If small floods have occurred for four consecutive years then sampling need only take place two years following the last small flood.

Sampling to test the model should occur within a year of any hydrological event (including droughts).

The best time for sampling in any given year is during low flow in September or October.

A summary of the data requirements for monitoring are summarized in table 8.3

8.4 USE OF THE DATA

There are three main groups that utilize data obtained from monitoring, namely, the model user (manager or researcher), the model developer (the model builder), and the decision maker (managers). Each of these users have a different use for the data.

- The model user may change estimates of variables and parameters should better data become available (see section 6.12.1).
- The model developer uses those data that address inherent assumptions and shortcomings in the model to test it, add rules or refine existing rules, and to recompile the model for the user.
- The decision maker is involved with the auditing of the TPC relative to the desired state of the river. The decision maker can use actual data to improve the accuracy of the TPC audit. Threshold values may need to be changed once they have been assessed. Decisions and action also need to be taken if the model predicts the TPC will be exceeded (Rogers & Biggs, 1999).

Table 8.3 Summary of monitoring requirements.

Motivation	Data Type	What to Sample	When to Sample	Where to Sample
ESSENTIAL DATA				
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

Chapter 9

A PROTOCOL FOR DEVELOPING RULE BASED MODELS AS DECISION SUPPORT TOOLS

Limited documentation of rule based modelling exists (Starfield *et al.*, 1990) to guide the inexperienced modeler. Some example models focus on conservation and wildlife management (Starfield & Bleloch, 1991) but none of them are specific to riparian systems. An important objective of this project was to develop a protocol using the literature and the experience we gained. This protocol aims to formalize, with hindsight, the sequence of events and processes used for the development, testing and use of rule based models as decision support tools for river management.

9.1 DATA NEEDS FOR Modelling

There are three important points about data availability and quality that we wish to convey in this protocol:

- you do not need data to begin modelling
- relevant data do improve confidence in models
- do not model simply to use available data

9.1.1 No data exist

The development of rule based models is useful whenever decision making is required, regardless of the amount and quality of available data. Developing rule based models forces scientists and managers to think about the problem to be solved, the decisions to be made, the components of the system, how they relate to each other and interact with one another. A basic understanding of the system derived from observations and literature is enough to define broad system states and use simple rules to describe how they interact. The most important step is to define the purpose of the model in the context of the problem and system characteristics.

9.1.2 Some data exist

While modelling is possible without data, the availability of data that are relevant to the model objective will improve the level of confidence that both developers and users have in its results and mechanism. A word of caution to model developers who are about to model where some data already exist: DO NOT build a model to use all the data simply because they are available. It is best to be aware of the data base and its potential, but the key to developing good rule based models is to adhere closely to achieving the objective of the model. Remember that these are problem-solving tools and a problem should be clearly defined. They should not be considered models with the sole purpose of explaining how systems function.

9.1.3 Acquiring additional data

In either of the above situations there will undoubtedly be the need to collect more data. Collection of the data should be guided by a) the problem or goal of decision makers, and b) an understanding of the system to be managed (even if it is only literature/observation based). For example, if the system is riverine and the problem is the impact of reduced flow regimes on biota, then the most likely data to collect would be hydrological, with descriptions of geomorphology and biotic assemblages (such as riparian vegetation or fish). If scientists or managers wish to collect data with which to model however, then it is best to build the best model possible under current resource constraints (section 9.1.1) and allow its assumptions, results and sensitivity to guide further data collection. The same principle applies to improving and refining existing models.

9.2 DEVELOPMENT OF RULE BASED MODELS

9.2.1 Planning the model

Effective planning is fundamental to producing a good pragmatic model. The success of this critical step depends mostly on clear definitions of problems, goals and objectives, and thorough conceptualization of the model components and their interactions. Pragmatic models are "purposeful representations" rather than "truthful representations" (Starfield *et al.*, 1990). In biological conservation, rule based models often make the best pragmatic models because:

- They do not require complete data sets or understanding of the system
- They reveal the logical consequences of their assumptions
- They are user-friendly, uncomplicated and have specific purpose
- Their operation is easy to understand and follow

The steps to developing rule based models as management tools are outlined in Fig. 9.1.

9.2.1.1 Problem and goal definition

Problem definition is a critical step to successful rule based pragmatic modelling. First the problem must be recognized as such by managers and scientists. Second, the problem must be simply defined in a manner which facilitates its analysis for solutions, but preserves all its critical elements. The management problem will usually be at a broad scale, in which case specific management problems need to be defined at finer scales (Fig. 5.4 for example). Specific management problems guide the development of management goals (Rogers & Bestbier, 1997), for example (Fig. 5.4), terrestrialization of the riparian zone (a specific management problem) leads to the management goal of assessing the ratio of terrestrial to riparian species in the riparian zone (the TPC for this problem). Defining the problem and goals is clearly a task that requires participation from scientists, managers and decision makers. It is certainly not the sole preserve of the model developer.

9.2.1.2 Being sure about objectives

The first direct step to developing rule based models, and possibly the most important, is to clearly define the objective of the model in terms of the goals of management. This step, together with problem and goal definition, will guide and influence all subsequent phases of model development (Jeffers, 1978; Starfield, 1997; this report). Model objectives must have the following characteristics:

- The objective must be appropriate to broader scale management goals or problems (Jeffers, 1978; Rogers & Bestbier, 1997) (TPCs in our example; Fig. 5.4).

- It must preferably be short and uncomplicated so that it is easily and clearly understood by developers, users and decision makers.
- Its aim is to guide the rest of model development, i.e. the model conceptualization, form and mechanism will closely adhere to the objective, so be sure to allocate sufficient resources and time to its definition.

9.2.2 Modelling

9.2.2.1 Model conceptualization

Once the objective of the model has been set, the developer can proceed to define the components of the model and how they relate to one another. This is done in conceptual form (Fig. 5.11 for example). The key to this phase is to constrain the number of model components and the complexity of interaction between them by allowing management goals to influence the pragmatic model world composition (section 5.3). Management goals "filter" ("TPC filter") our current best understanding ("Entire system model world") to produce a pragmatic conceptual model ("Pragmatic model world") (Fig. 5.2). For example, it is a management goal to maintain sufficient exposed bedrock influence in the Sabie River (Fig. 5.4), so we used a single riparian species as an indicator of bedrock (rather than a suite of riparian species), and only included components that were needed to effectively model the population dynamics of this species (Fig. 5.3). (See sections 5.3, 5.4.2, 5.5.2 and Fig. 5.11 for a detailed example of model conceptualization). In this way model conceptualization is aimed at being relevant to management problems and goals, and as simple as possible without leaving out critical elements in the model. During this phase, it is important for the developer to assess and be clear about:

- Specific model characteristics such as whether it should be deterministic or stochastic, spatially explicit or not, or include specific functions to enhance it e.g. matrix techniques.
- Whether the right questions are in fact being asked.

9.2.2.2 Building the model engine and interface

In this phase the model rules are defined and coded to transform the conceptual framework into a working model. It is important to ensure that the working model faithfully portrays the

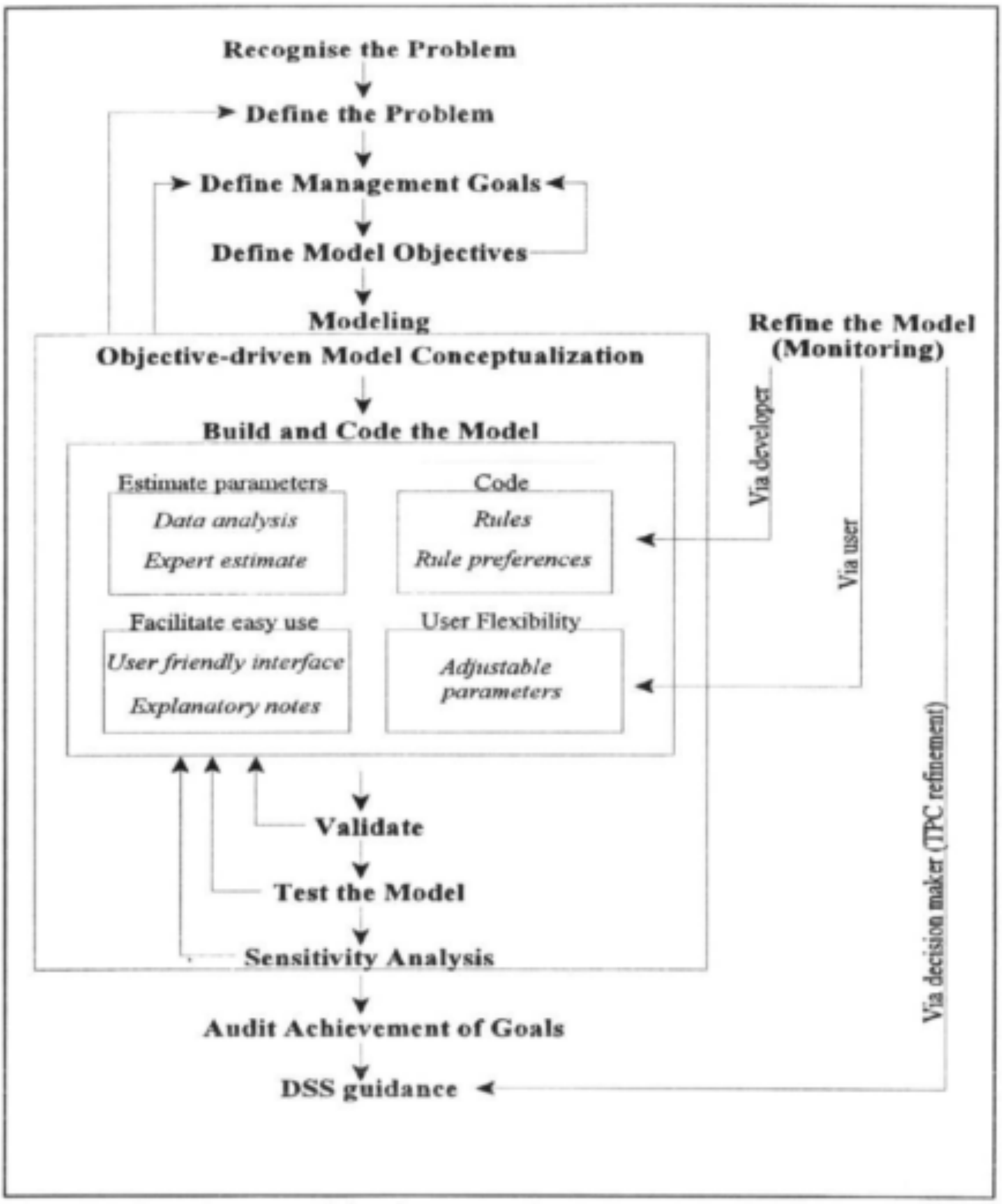

Figure 9.1 Flow diagram outlining the steps to developing rule based models as management tools.

pragmatic conceptual model. Coding must incorporate feedback mechanisms and model assumptions, as well as the complexity of the rule series that will be used to reach decisions about management actions. Parameter estimates are calculated from data if data are available and applicable, and where not, they are estimated by expert opinion.

Rules are IF/THEN statements, that when strung together invoke a causal chain of reasoning to produce a particular outcome. IF/THEN statements can be composite where a number of AND statements are used in a rule statement to combine the influence of multiple factors. An example of a series of rules statements used in the matrix construction of the *Breonadia* model:

> IF Adult Density is High AND a Large Flood Event is False AND a Small Flood Event is False AND a Drought is False AND a NoFlow Event is False AND a Catastrophic Flood Event is False THEN
>
> In Row 1 and Column 6 of the matrix for actively flooded Mud/Silt = The Fecundity under no event conditions * 0.6./ (1 + (Starting population size) * Fecundity under no event conditions))
>
> ELSE IF Adult Density is High AND a NoFlow Event is True THEN
>
> In Row 1 and Column 6 of the matrix for actively flooded Mud/Silt = The Fecundity under NoFlow event conditions * 0.6./ (1 + (Starting population size) * Fecundity under NoFlow event conditions))
>
> ELSE IF etc.
>
> END IF

The choice of interface between the model engine and its users is important because it will influence its acceptance by managers. We chose to code the model in Visual Basic because:

- It makes full use of the Windows environment which is familiar to users
- It provides a user friendly interface which is graphically pleasing and makes it easy for the user to follow what happens
- Visual Basic results in event driven programs where the user is required to perform certain actions to invoke events (or procedures), rather than programs where the code runs in sequence with no user control.

A word of caution to developers is that at this stage it is easy to get carried away by perceptions of the ingenuity and elegance of the model. Be sure that this does not result in the loss of contact between the reality of management and the rules and mathematics that determine the possible consequences of decisions. Adhere closely to the model objective!

HELP facilities in the form of explanatory notes further facilitate use of the model by decision makers and improve their level of confidence in the model mechanism. We have included explanatory notes in the *Breonadia* model that the user can view at any time. These include help menus and text boxes that introduce the model and management goals (TPCs), outline model rationale, explain model use (such as input scenarios, default settings and how to change them, interpreting outputs and using TPCs).

Possibly one of the most important characteristics of the *Breonadia* model is that parameter estimates are not hard coded into the model engine, but are read from a set of suggested default settings which the user can change. This affords the user flexibility, not only to manipulate parameters for model exploration and scenario evaluation, but also to permanently update parameter estimation (see section 9.2.5.1). We suggest that this is one of the best ways to model with parameter estimates that have low levels of confidence. Rather than excluding them, it provides an advantage of easy refinement.

9.2.3 Improving confidence in the model

Once the model has been brought to the phase where it can be run and produces output, it can be used to evaluate potential management actions. It is first necessary however, to investigate the sensitivity of the results of the assumptions made in the model, as it is only when the model is used that previously unsuspected weaknesses in the assumptions and in the model formulation and accuracy are revealed. This involves three aspects, validating, testing and sensitivity analysis.

9.2.3.1 Validating the model

Validating and Testing the model are often seen as one and the same (Starfield *et al.*, 1990). We distinguish between them as two separate and necessary tasks. Validating the model means making sure that invoking rules in the model produces the correct response (section 7.1). For example, if a rule requires survival of seedlings to be set to zero following a catastrophic flood, then validation will involve running a scenario in which a catastrophic flood occurs and checking to see whether the seedling survival has in fact been set to zero. All rules need to be validated in this way. Attention must also be given to checking rule preference, that is, one rule may need to take preference over another if both are invoked. For example, if a large and small flood both occur in the same year in the *Breonadia* model, rules pertaining to large floods take preference because they have an overriding effect on model response. These kinds of rule interactions need to be verified in the model.

9.2.3.2 Testing the model

There are two conventional, direct ways of testing a model (Starfield *et al.*, 1990). The first is to collect a new set of data against which the model output is tested, and the second is to keep some of the original data that were used to develop the model aside, specifically to be used later on to test the model. In rule based models where no or limited data have been used, testing the model is less straight forward (Starfield *et al.*, 1990) and indirect ways must be used. These include simply validating the model as in section 9.3.1, or checking modules or the entire model to see if behaviour is acceptable (Starfield & Bleloch, 1991). We tested our model in this way by running various scenarios and using expert opinion to confirm that results were realistic and in keeping with understanding (section 7.3). Where data are available, direct resting is preferable, although indirect testing can highlight inadequacies in the model. We found that indirect testing led to a number of improvements in the *Breonadia* model.

9.2.3.3 Sensitivity analysis

A sensitivity analysis should to be conducted to assess model response to parameter changes. This is systematically done in either a uniform or variable way, testing either single or multiple parameter changes (section 7.4). Usually, single parameter sensitivity analysis is sufficient in deterministic, linear rule based models (Starfield & Blelock, 1991). We calculated a sensitivity index (S) from model output (in this case population density for each of 6 classes) before and after the parameter change, as well as values of the parameter being tested, before and after its change (Haefner, 1996):

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

where R_a and R_n are model outputs i.e. 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. It was found that a negative and positive value (eg an S-value of 0.379 and -0.379) indicated equal levels of sensitivity. The results of sensitivity analyses are used to:

- Further validate the model, by evaluating extreme responses to small changes
- Outline research priorities, by focusing on the most sensitive parameters first
- Elucidate potential system controllers, indicating which sensitive parameters are also potential management tools
- Direct the development of monitoring programmes (section 7.4.4), to collect data for sensitive parameters only.

9.2.4 Decision support

Decision support and decision support systems in the KNPRRP context have received much attention and have been the focus of much investigation (Rogers & Bestbier, 1997; Rogers & Biggs, 1999). These authors outline a protocol for a goal maintenance system, which involves achieving, auditing, revising, reintegrating, and actively communicating the goals. The role of models in this protocol is to predict the consequences of management actions and to audit achievement of the goals based on that particular action. The last steps required to develop good rule based models as management tools involve auditing achievement of goals to subsequently guide decision support.

9.2.4.1 Audit achievement of goals or objectives

The key to pragmatic modelling is that it serves a purpose for management. This means that it would be advantageous to have built-in features which support decision making beyond simply generating numerical output. Models should have a mechanism for auditing the achievement of goals or objectives. For example, the *Breonadia* model analyses outputs to determine threshold values and graphically indicates where thresholds are exceeded (see section 7.2). These thresholds are in the form of TPCs, which are the management goals (Rogers & Bestbier, 1997). The model graphically indicates where and when management goals are not achieved for the chosen scenario. Managers are therefore able to determine whether their actions will produce the desired goal, based on the model prediction. These predictions for different management scenarios are used in the next step to guide decision making.

9.2.4.2 DSS guidance

This step involves using model predictions of biotic response as well as goal achievement, to assess the potential of alternative management actions to meet management objectives and goals. This step is the ultimate reason for building the model in the first place, and is an input to the decision making process (Rogers & Biggs, 1999).

9.2.5 Further improvement of the model

Remember that the model is a systematic sequence of assumptions, and as such will certainly require refinement in some areas at least. This can be done in any of three ways:

9.2.5.1 By the user

The user of the model can refine the estimates of model parameters and variables. This is done directly in the model utilizing data that have been collected in the monitoring programme (see chapter 8). The user should also give feedback to the developer concerning areas in the model that need to be improved.

9.2.5.2 By the developer

The developer of the model can refine the rules and rule preferences by altering the model code. Additional rules can be added to address current assumptions in the model. Once again, data from the monitoring programme, or the results of other, directed research, can be used.

9.2.5.3 By decision makers

Decision makers can also refine the model in that they can improve the critical values of the thresholds i.e. refine the TPCs. The process of TPC refinement is well outlined by Rogers and Biggs (1999).

Chapter 10

CONCLUSION

The *Breonadia* model has value as a management tool because it:

- Predicts the population response of *B. 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 presentations of results.
- Has explanatory notes and HELP facilities.
- Is pragmatic in that it addresses management goal audits for the Sabie River.

10.1 PREDICTION CAPABILITY

Major management problems along the Sabie River are decreased flows and alluviation of the macro-channel. The *Breonadia* model predicts an unstable and 'unhealthy' population of *B. salicina* when flows and exposed bedrock proportions decline. The rate at which the population becomes a management concern depends on the rate of flow and bedrock reduction, and the exact values of TPC parameters. Prediction capability will be increased by improving hydrological and geomorphological interaction scenarios, and precise definitions of TPC parameter values.

10.2 DECISION SUPPORT

Audits of the TPC are graphically presented with population size class density and input summaries, which enable interpretation of causes for TPC exceedence. This, together with a formal protocol to guide the use of TPC audits, effectively supports decision making. TPC exceedence objectively warns managers and decision makers of the likelihood that goals will not be achieved, and prompts either TPC refinement or management action.

10.3 REFINEMENT OF THE MODEL

The future challenge for management is to ensure iterative use and refinement of the *Breonadia* model. Effective refinement will depend on post-use interaction between developers and users, where users provide feedback of model operation and shortcomings. A proposal for the project entitled "Rule based modelling of riparian vegetation and technology transfer to enable strategic adaptive management of Kruger National Park Rivers" has been approved by Water Research Commission for commencement in 1999. Implementation of a monitoring programme (chapter 8) will provide necessary data with which to test and refine the model.

10.4 TECHNOLOGY TRANSFER

The *Breonadia* model is a predictive tool for management of the Sabie River, and was effectively developed in a data poor environment by taking a pragmatic rule based approach to modelling. The expertise gained from, and the approach used in this project are transferrable to other riparian systems. A protocol has been outlined (chapter 9) that guides the application of a pragmatic rule based modelling approach. Guidelines are general, but illustrated by way of the example presented by this project.

10.5 APPLICATION TO WATER FOR THE ENVIRONMENT

Legally, only one right to water is specified in the National Water Act; that of the Reserve (White

Paper, 1997; National Water Act News, 1999). The Reserve consists of two parts:

- **The basic human needs Reserve**, which includes water for drinking, food preparation and personal hygiene.
- **The ecological Reserve**, which must be determined for all or part of any significant water resource such as rivers, streams, wetlands, lakes, estuaries and groundwater.

The Reserve must specify the quantity and quality of the water which will maintain the resource in an ecologically healthy condition and provide the basic human needs for water. All water uses under the National Water Act are subject to the requirements of the Reserve. Thus, licences for different types of water use cannot be issued without the Reserve having been determined.

Managers of a water resource are therefore faced with the task of determining the ecological Reserve in their area. All other uses of the water resource are then authorised according to the criteria of equitable allocations, beneficial use in the public interest, and promoting environmental values. These allocations are the responsibility of Catchment Management Agencies, in which conservation managers are usually involved. The difficulty of quantitatively justifying water demands for environmental use has weakened the bargaining power of conservation. Biologists and conservationists quantify water demands (justifiably so), with difficulty due to the complex nature of the systems they represent and manage and are therefore in need of tools such as the *Breonadia* model, that serve to quantitatively address the desired state (Rogers and Bestbier, 1997) of rivers in the catchment by being able to determine and justify the ecological Reserve.

The *Breonadia* model has three main targets: researchers, managers and policy makers. Researchers will use the model to highlight sensitive parameters and direct research efforts to improve the accuracy and reliability of model outputs and assumptions by improving the estimation of sensitive parameters. Model reliability and validation will also be improved by employing the proposed monitoring programme, so that the model can be tested against recorded data.

Managers will use the model to run TPC audits of scenarios of potential management actions, for example planting trees along the river, and scenarios of catchment developments, for example altered hydrological regimes due to dams, so that they can assess goal achievement under specified conditions. This will enable them to ascertain when to apply management actions, for how long, and to determine which actions might result in the maintenance of the desired state. Managers will also be in a better position to influence policy development and licenced allocations of the water resource by using model audits to justify the ecological Reserve.

Policy makers will not necessarily use the model, but they do exert marked influence on rivers and catchments. Policy makers can be shown with confidence, the justified requirements of conservation (the ecological Reserve), and it can be demonstrated to them, that prediction is achievable. When policy is then formulated it should be based on and incorporate, amongst other things, prediction.

In the KNPRRP context, and specifically in the Sabie River catchment, the *Breonadia* model, though specialized in its application, empowers conservation managers around the bargaining table of catchment role players. The model is essentially a river-section-scale tool (quantitative solicitation of a causal chain of our assumptions) that can be applied to catchment-scale decisions, actions or policy, by explicit definition, justification and consideration of the ecological Reserve for the Sabie River.

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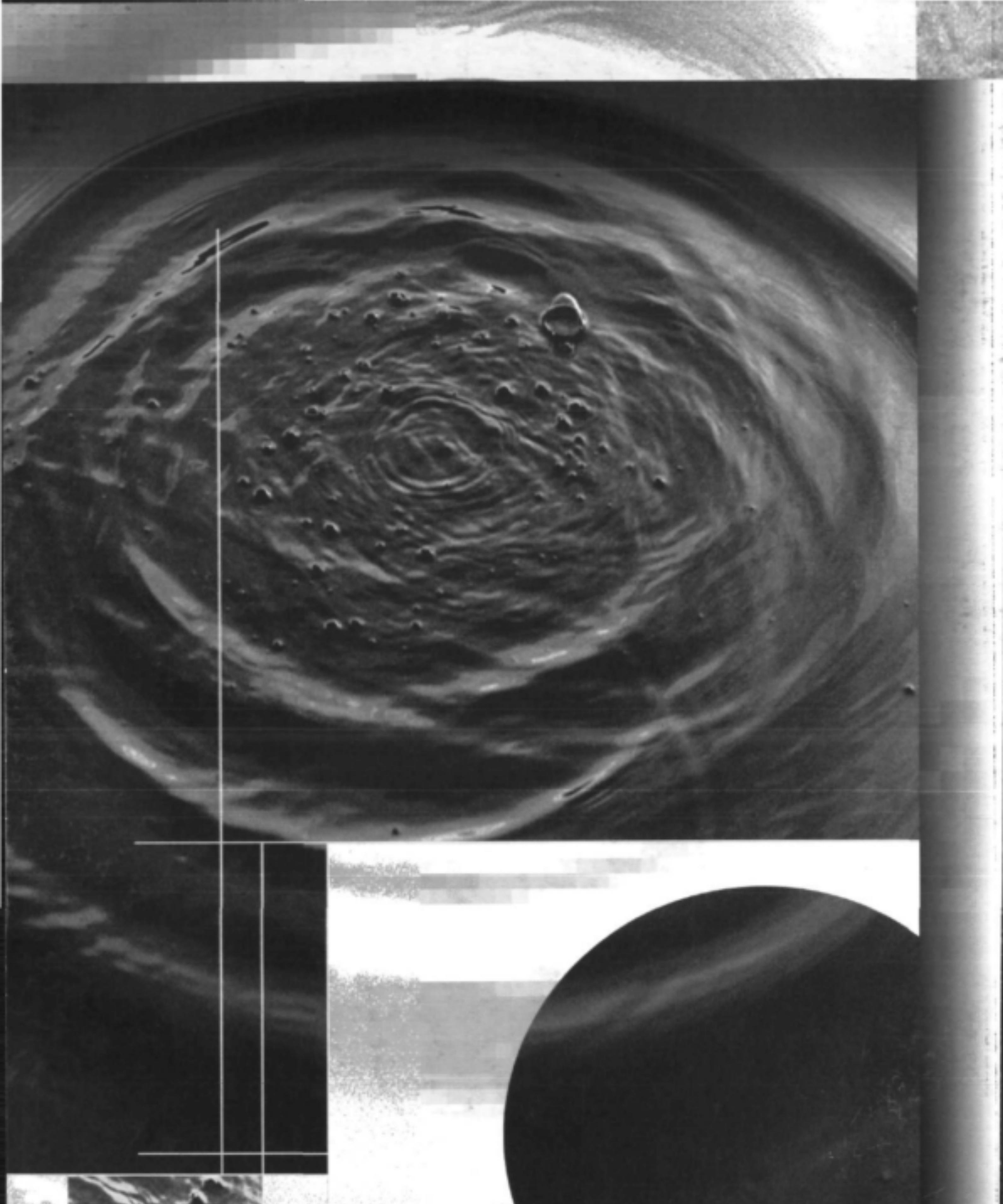

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