OPERATIONALIZING MULTI-PARTY STRATEGIC ADAPTIVE MANAGEMENT (SAM) OF THE SABIE RIVER

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By

KH Rogers

Centre for Water in the Environment
University of the Witwatersrand
Private Bag 3
Wits 2050, Johannesburg
South Africa

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Executive Summary

Introduction

The aim of the project was to achieve a working relationship between the main parties involved in managing the Sabie River. The context was that, through the auspices of the Kruger Park Rivers Research Programme (KNPRRP), managers in the Kruger Park had developed a set of conservation management objectives and goals (Thresholds of Probable Concern: TPCs). Co-operation between all managers within the Sabie River catchment would be needed to meet those goals. The "main players" were DWAF, KNP/SANParks, DEAT, a "catchment management agency", researchers of the KNPRRP and the River Health Programme.

The project was a major learning experience because it was the first attempt at co-ordinating water management around the issue of "environmental flows" or the "reserve" for a particular river. An implicit objective of the project was to ensure that KNP management could operate independently of the KNPRRP, as the latter was in its final phase and was due to be closed within a year. KNP management had been very dependent on the KNPRRP expertise, and it was time to set the weaning process in motion.

From the initial discussions with DWAF and KNP managers it was clear that without a crisis for them to manage, it would be very difficult for an outsider to initiate procedures for Strategic Management at a catchment scale. A study by Birkhead et al (2000) revealed that the environmental flows proposed by the "Instream Flow Building Method" were unlikely to meet the KNP objectives, and the geomorphology TPC would be exceeded. However, KNP managers did not accept these conclusions, despite the fact that the study supported a mature hypothesis developed from many projects, over many years of research. In contrast, the scientists did accept the conclusions, leading to fruitful interactions and the main substance of this report.

It was decided, in consultation with the KNPRRP management committee, that the strategy for the project should be to:

- challenge KNP managers with the full history of scientific studies leading to, and including those of Birkhead et al, and thereby "create a crisis" to which they had to respond,

- scientists would then monitor the nature of their response and engage them in discussion on how to formalise procedure for broader future use,
- use collaboration between scientists to develop conceptual frameworks with which to engage managers in environmental water management.

The Challenge to KNP managers: purpose, process and nature of response

Because resource management is often performed by bureaucracies, real change in management style, purpose or strategy often only occurs in response to a "crisis" (Gunderson et al, 1995). Indeed, the new Strategic Adaptive Management programme in the Kruger Park arose in response to two "crises":

- the general social revolution in South Africa,
- pressure from animal rights activists to change the elephant management policy.

It was decided to engineer a "crisis" amongst KNP management to precipitate a "reaction" to the scientific findings, by sending a formal letter explaining the long history and compelling evidence of scientific research. The letter stressed two issues. Firstly, that certain river TPCs would be exceeded, and therefore the desired state of the Sabie River will not be met, and secondly that the KNPRRP was coming to an end and that the KNP needed to be weaned from it.

Summary of the letter

- There is a general sequence of succession in the KNP rivers in which water and rock are covered by sand, which is colonized by reeds, followed by bushes, and finally trees. The likelihood of flood disturbance resetting the system and maintaining a diversity of habitats decreases as succession progresses. In the Sabie River a directional change towards natural riparian forest began in the late 1960's, coinciding with development of commercial forestry in the catchment.

- A high diversity of geomorphic features in the Sabie River arises from a mixture of alluvial (sediment) and bedrock characteristics, and a variable flood regime which creates a complex pattern of erosion and deposition in space and time. A study by Heritage et al (1997) inferred that the sediment transport capacity of the river is being reduced by increased sediment load and decreased water supply, and that this would result in reduced diversity of physical features as sediment accumulates.
- There is a positive correlation between species distribution and diversity of geomorphic features. Thus a loss of bedrock from increased sediment storage will result in a loss of structural and compositional diversity as many species are dependent on bedrock habitats. A loss of functional diversity will follow.
- The KNP objectives hierarchy was built on this information base. Limits were placed on the degree of bedrock loss and vegetation response which would indicate that the desired state would not be met. This TPC would warn management that the system was on an unacceptable trajectory of change, prompting action before it was too late.
- Birkhead et al (2000) modelled the physical response of the Sabie River to a range of hydrological and sediment input scenarios and predicted that provision of the Instream Flow Requirements for the Sabie River (Tharme et al 1996) would result in progressive long term sediment accumulation and therefore a loss of bedrock influence. The desired state of the Sabie River will thus not be met by the IFR.
- Mackenzie, van Coller and Rogers (1999) developed a model to predict *Breonadia salicina* response to changing conditions. The model predicts that the *B. salicina* TPC will be exceeded under the sort of sediment scenario described by Birkhead et al.
- Scientists are concerned that management was hampered by old ways of thinking and, for example, would react to the death by poaching of single elephant or rhino but could not respond to an ecosystem level warning of future problems.
- Many problems of river management originate outside the KNP, and become problems of catchment which cannot be solved by the KNP alone.
- The results of ten years of peer reviewed, collaborative research should be more than sufficient for KNP personnel to take appropriate action.
- The KNPRRP is about to end, and the KNP must be weaned from it. All the data and models resulting from the KNPRRP are available to KNP personnel.

KNP Managers' Response

The high standard, relevancy and scientific rigour were often hailed on different forums. The scale of the sediment problem, the socio-political nature and complexity thereof, and the uncertainty about the real origin of the sediment made it difficult for KNP management to get into top gear straight away.

The floods of February 2000 had a major influence on the unfolding (or lack thereof) of actions later on. Following the floods the urgency for this TPC diminished as other priorities such as the financial crisis emerged and the urgency to get tourist facilities, roads and bridges fixed and start generating an income again

Another factor that had a considerable influence on KNP management was the energy that went into engaging the CMA development process at that stage. KNP champions were nominated to represent the KNP on each of the Olifants, Sabie and Crocodile river CMC's. Apart from the usual bargaining for water rights, a spirit of co-operation often characterized these meetings (like the old days with the Sabie River Working Group and Olifants River Forum). There was a feeling of anticipation that drafting a CM Strategy would be a great and rewarding experience that could bind stakeholders together and tap into the KNPRRP knowledge bank to tackle many of the catchment problems.

Conceptual frameworks of science management interaction in environmental water management

Interaction between scientists from the Centre for Water in the Environment (University of the Witwatersrand), River Health Programme (CSIR) and Kruger National Park led to three frameworks for science/management interaction.

Framework 1: Operationalising Strategic Adaptive Management in the Kruger Park

In an effort to operationalise the notion of sustainable ecosystem integrity, ecologists have focussed on identifying sets of indicators which can be used to assess river condition relative to some normative, undergraded condition. Effective river management depends on an operational definition of the desired system condition that reflects both scientific rigour and broader societal value systems. It is critical that rivers are managed, and not merely monitored. Ecosystem "endpoints" provide a scientific description of management goals, and "values" provide a societal perspective. Together they complement the use of indicators and provide a strategic, rather than a reactive, approach to management.

An Objectives Hierarchy has been developed for the rivers of the Kruger Park, to service management's institutional hierarchy. A "Vision" provides upper levels of management with value based statements of strategic intent, and goals provide managers on the ground with specific ecological endpoints. Thresholds of Probable Concern (TPCs) represent statements or hypotheses of limits of acceptable change in ecosystem structure, function, and composition. Integrated monitoring, research, and modelling track criteria relative to TPCs to determine whether management action, or recalibration of the TPC is needed. Thus TPCs provide direction for management, and their validity is frequently questioned and modified.

The Objectives Hierarchy mandates Kruger Park management to "....maintain biodiversity in all its natural facets and fluxes...". Alluviation is a threat to the biodiversity of bedrock controlled rivers such as the Sabie River. TPCs for geomorphic diversity thus reflect permissible ranges of change in the proportion of bedrock in the physical template. TPCs for riparian vegetation, measured as change in population structure of selected species, reflect a likely range of biotic response to change in the physical template. These TPCs therefore provide a parsimonious programme to assess ecosystem state relative to management goals and prompt appropriate action.

Framework 2: Challenges for operationalising SAM in catchment management agencies

Catchment management agencies (CMAs) are faced with a challenging task as there is no tested precedent in South Africa, and they will have to evolve in complex and changing business, social and natural environments. They will aim at ensuring that equity and social justice are achieved within ecological limits.

The "command and control" management used in the past was only successful in the short-term, as reducing natural variation causes the ecosystem to lose its resilience and ability to recover from disturbances. There are various lessons we can learn from past experiences. The first is that the long term consequence of command-and-control management is always either a reduction or cessation of resource supply. The second lesson comes from adaptive resource management (ARM), which encourages a learning-by-doing approach to compensate for managers' poor understanding of ecosystem functioning. The third lesson deals with the flouting of the fundamental management axiom "form must follow function", which has thwarted many attempts at adaptive management. Lesson four is that "learning institutions" are replacing authoritarian, command and control bureaucracies which are unable to respond rapidly to a changing environment. Lesson five states that effective knowledge management is critical for successfully converting command-and-control management into adaptive, learning-by-doing management. These lessons must be applied by CMAs, so that they can integrate stakeholder values and activities within ecological limits, using an adaptive and generative management approach.

Strategic adaptive management (SAM) is a local derivative of ARM designed to generate consensus management which is inclusive, strategic, adaptive and creative. It is a process in which effective knowledge management is central to building a partnership between science, management and society to achieve a common vision, and thus has considerable potential for application to CMAs.

Framework 3: General principles and process of SAM

SAM is defined as a process of managed learning which steers strategic action to achieve desired ecosystem end points. It hinges on the axiom that ecosystems are "complex dynamic systems". The three components to a SAM operation are research (conducted by integrators), interfacing (conducted by networkers), and an institutional system (steered by generative leaders).

Ensuring that science is used in management and vice versa is the essence of SAM. It is based on the following four premises. The first is good, multi-scaled science under a paradigm of ecosystem flux. Research must be directed at understanding ecosystem change and the agents of that change, and must be based on ecosystem management goals. The second is a science/management partnership based on shared vision, needs, values, ecosystem end points and reward system. The third is defined behaviour of the implementing institution, which is usually the management institution as science generally operates outside the implementing agency. Strategic knowledge management is achieved by generative leadership in a culture of shared purpose and institutional learning. Appropriate individual behaviour is the fourth premise, and encourages individuals to acknowledge the importance of each person's role in effecting change.

There are a number of important "don'ts" when applying SAM. These include not focussing on predefined products or on predefined procedure, but on flexible process and outcome. Do not try to transfer research findings directly, but transform them into technology first. Do not transfer technology to the user organisation, but diffuse it into the organisational system. Use whatever resources you have to formulate hypotheses that can be tested in an adaptive management process, rather than complaining about the lack of sufficient resources.

Lessons for future management operations and technology transfer

Lessons learnt for improving the operations in the Kruger Park (with general implications)

1. The response to problems in resource management is critical, and should always include both "event" and "strategic" responses.
2. There is generally poor data capture from events, and this needs to be improved and incorporated into organisational knowledge management structures.
3. Resource management organisations need to provide guidance for "action taking", and not only for "problem solving".
4. Goal orientation must become entrenched in response guidance. Goals are the essence of strategic management and must be used in hypothesis testing.
5. Resource management organisations need to become learning organisations, and leaders

need to become generative in their approach.

Lessons learnt about improving the management of technology development and transfer

1. Technology transfer should not be a one way process of researchers sharing information with the client, but must include complimentary activities of diffusion of technology into the organisation and adoption of the technology by the organisation.
2. Applied research projects should only be funded when both the research organisation and the client take responsibility for technology transfer and adoption. Funding agencies should provide rewards for successful technology transfers.
3. To evaluate a proposal, certain important questions should be asked. These include questioning if the idea was good, whose idea it was, if the product was wanted, who wanted it, and if it would make a good research project.
4. To evaluate the success of a project, various questions should be asked. These include was the product useful, did it work, was it used, and did it evolve into something better with time.
5. Certain corollary questions to be considered:

- Is your project about managing the research process, management process, technology transfer process, or the adoption process?
- Were you looking for an idea, problem or solution?
- Were there reciprocal social contracts between researchers and managers/users?

Conclusion

At the time the project was initiated it seemed it would be quite feasible to link up river management in soon to be established catchment management agencies and the downstream Kruger Park management system. However, formal catchment authorities have not been formed and DWAF, which acts in their stead, has no history of or capability to manage river ecosystems. Its capacity remains in managing water storage, transfer and off channel delivery. Changing this has required major change at national level beyond the scope of this project. This project has however made important contributions to the Kruger Park management system and conservation managers are much more capable of responding to river management problems. Lessons learned during this process have led to the publication of insights to and recommendations for future catchment management agencies. Overall the project has been an important contributor to a new resource and conservation management system which is recognised and envied internationally as an innovative application of modern thinking.

Acknowledgements

David van der Merwe, Charles Breen and Steve Mitchell of the KNPRRP provided much needed understanding, guidance and support for this project. Harry Biggs' unfailing commitment to Strategic Adaptive Management was a tower of strength during the project. Under his guidance SAM will go from strength to strength in Kruger. Dirk Roux, Freek Venter and many others have given freely of their experience and knowledge to much enrich my experience of SAM. Wendy Midgley and Debra Jackson provided excellent logistical and administrative support.

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Chapter 1
Introduction

As the title infers, this project was aimed at achieving a working relationship between the main parties which should be involved in managing the Sabie River. The context was that, through the auspices of the Kruger Park Rivers Research Programme (KNPRRP), managers in the Kruger Park had developed a set of conservation management objectives and goals (Thresholds of probable concern; TPCs). Meeting these goals would require co-operation from the "main players" in the water management arena within the Sabie River catchment. These players were envisaged as DWAF, KNP/SANParks, DEAT, a "catchment management agency", researchers of the KNPRRP and the River Health Programme.

The original proposal described the **product** of the project as:

> *An operational Strategic Adaptive Management system for the Sabie River and a protocol which could be used by catchment management agencies to ensure that management goals are achieved and audited.*

The **objectives** which would lead to this product were:

> *Establish and implement procedures for integrating modelling, monitoring and decision making in multi-party management of the Sabie river*

> *Ensure this implementation elicits appropriate responses and actions from the decision makers, managers and researchers who should be involved in management of the Sabie River.*

The **methodology** was to:

> *Conduct interviews and/or work sessions with appropriate managers, collaborators and researchers, especially from KNP and DWAF to establish lines of communication and*

procedures for management.

The project **implementation strategy** was to achieve the following 8 tasks in sequence:

- *Evaluate current monitoring procedures and their potential to assess and contribute to, achievement of the Desired State/Thresholds of Probable Concern for the Sabie River.*
- *Evaluate current modelling capabilities and their potential to predict the Desired State/Thresholds of Probable Concern and river health for the Sabie River*
- *Evaluate compatibility of the DWAF River Health Monitoring Programme and the KNPRRP Desired State monitoring programme and develop a strategy for integrating the two.*
- *Evaluate the current status of monitoring and modelling results and their implications for achievement of the Desired State/TPCs, with particular reference to Birkhead et al.'s prediction that the geomorphology TPC will be exceeded by the proposed Sabie River IFR.*
- *Determine which parties (research, management and monitoring) are responsible for making which type of decision in response to predictions that TPCs for Kruger Park rivers will not be met.*
- *Determine information needs of these parties and the pathways of information transfer which will lead to response by them to predictions that TPCs will be reached and therefore that the Desired State will not be achieved.*
- *Using particular TPCs as examples, gather the appropriate information and elicit appropriate operational responses from these decision making parties to close the research, monitoring, management loop.*
- *Document the process and derive protocols for use in future catchment management operations.*

This project was a very first attempt at co-ordinating water management around the issue of "environmental flows", or the "reserve" as it is now known, for a particular river and became a major learning experience. The project had another implicit objective and that was to ensure that KNP management could indeed operate independently of the KNPRRP. The KNPRRP was in its final phase and was due to be closed down within a year. KNP management had been very dependent on the KNPRRP expertise and it was time to set the weaning process in motion.

From the very first attempt to discuss issues with DWAF and KNP managers, it became clear that unless there was a crisis to manage, it would be very difficult for an outsider to capture their attention and to set up procedures for Strategic Management at a catchment scale. This was despite the fact that Birkhead et al (199?) had demonstrated the likelihood that the environmental flows proposed by the "Instream Flow Building Block Method" would not meet the KNP objectives and the geomorphology TPC would be exceeded. The reasons were three fold;

- DWAF does not actually manage **rivers** but the storage, abstraction and supply of **water**. Thus, despite new legislation, the Department did not have the structures or mechanisms to deal with these issues of environmental flows. An extraordinary event or issue would have to arise before the need to engage river management was appreciated.
- The expectation that there would be something such as a "catchment management authority/agency" so soon after the new legislation was passed, proved naive. The people or institution which would manage rivers therefore did not exist and could not be interviewed.
- Although a new strategic adaptive management approach had been designed for the KNP and adopted in early 1999, it became clear that institutionalising it would be a much more complex task than anticipated. Old habits of monitoring without clear goals, and a predilection to crisis management, still dogged the organisation. Managers were unable to independently accept scientific findings (e.g. those of Birkhead et al) and translate them into management decisions. When Birkhead et al's findings were presented to the Standing Committee for Conservation (KNP) its members decided they could not react to a single study and questioned its validity. This despite the fact that they, and their advising scientists, should have been aware that Birkhead's study supported a mature hypothesis developed from many projects, over many years of research.

There was an altogether different reaction from scientists in the KNP (Dr H Biggs) and River Health Programme (Dr D Roux, CSIR) who gave their full support to the author (KNPRRP) leading to very fruitful interaction and the main substance of this report.

The inability of managers to independently react to scientific findings, and the lack of river managers upstream of KNP, meant that the original tasks proposed for this project had to be rethought and an altogether different strategy developed. It was decided, in consultation with the KNPRRP management committee that this strategy should be to:

- Directly confront and challenge KNP managers with the full history of scientific studies leading to, and including, those of Birkhead et al and thereby "create a crisis" to which they would have to respond.
- Scientists would then monitor the nature of their response and engage them in discussion on how to formalise procedure for broader future use.
- Use collaboration between scientists to develop conceptual frameworks with which to engage managers in environmental water management.

Chapter 2

The Challenge to KNP managers: Purpose, process and nature of response

2.1 Introduction

Gunderson, Holling and Light (1995) have provided an intriguing insight into the vast array of factors which limit or promote adaptive environmental management in a book entitled "Barriers and Bridges to resource management". One extremely important finding was that in every case study examined real change in management style, purpose or strategy only occurred in response to a crisis of some sort. The scale of the crisis needed was dependant on the magnitude of change needed. Such crises can be surprises or can be engineered to effect change. The new Strategic Adaptive Management programme in the Kruger park arose in response to two crises: The general social revolution in South Africa and the pressure from animal rights activists to change the elephant management policy.

The inability of KNP management to independently react to scientific findings within the ambit of their new management framework needed a much smaller "crisis" which could be "engineered" by means of a formal letter explaining the long history and compelling evidence of scientific research. The letter and attachment are reproduced below.

2.2 The Letter: A Challenge to KNP managers

Dear All

Following my visit to the park last month I have drawn up a document which outlines the issue I am/we are dealing with in respect of river TPCs which will be exceeded. I am also, I think, somewhat unequivocally laying down the gauntlet to KNP.. As I state in the document, the KNPRRP is dying and it is time to very rapidly wean the KNP off the KNPRRP. I guess it has fallen on me to precipitate that weaning process through my project to close the research/management/monitoring loop. Well, if it hasn't fallen on me I have been presumptuous enough to take it on. Knowing full well that there may be some painful times ahead.

I do hope my synthesis and cajoling below will have the desired effect of precipitating a horrified response (There goes that Rogers again!) but can be taken in the constructive way it is intended.

Put very simply I don't think the Standing Committee response to notification of TPC problems in the Sabie is appropriate if you consider that the weaning process has 6 months to go. So like the mother who is running out of milk I have pushed the young one away and said come back prepared to fight me for it - but I will nurse you along for a while.

To be more direct - we have known for more than 6 years that the rivers are in trouble and why. We have only been getting more and more sure of it. It is not appropriate that the essence of the response should be to ask for more info as a first step. I have tried to explain why this is so. Hope it works.

Regards
Kevin

2.3 Synthesis of problem: The desired state of the Sabie River will not be met: what now?!

2.3.1 Sequence and source of information

1. Carter and Rogers (1989, 1995) examined the 50 year aerial photographic record and demonstrated a general succession sequence in the KNP rivers. Water and rock were covered by sand which was colonized by reeds, then bushes, followed by trees. As the succession progresses the likelihood of flood disturbance resetting the system becomes less. A forested river landscape is therefore much less likely to revert back to a rocky channel with wide water bodies, than a sand bank recently colonized by reeds. Similarly as a river becomes more forested the likelihood of flood disturbance creating open water and sand bank habitat becomes less. Another way of stating this is that as a river becomes more forested, larger and larger floods are needed to reset it. This study also illustrated that in the Sabie river this directional change toward a forested system began in the late

1960's. There was much change in river condition prior to this but it was more random between the states mentioned. The switch to more directional change coincided with forestry development in the catchment but no definite statement of cause and effect can be made. The Letaba River showed a reverse trend to a more sandy condition (that is increased sediment storage) over the same period and this might be correlated with the very marked flow reductions seen during this period.

2. Heritage et al (1997) described the historically very high diversity of physical geomorphic features in the Sabie and Letaba rivers. This was attributed to the mix of alluvial (sediment) and bedrock features in these semi-arid rivers, and to the variable flood regime which creates a complex pattern of erosion and deposition in space and time. This alluvium/bedrock mix (also seen in the Olifants and Crocodile) is a consequence of (i) recent geological upliftment which means the river has cut to bedrock, (ii) most flow being generated high in the catchment and (iii) most sediment being produced in the semi-arid landscape further down stream. Their study inferred that sediment transport capacity of the river was being reduced by increased sediment load and decreased water supply, and that this would lead to a loss of diversity of physical features as sediment accumulated. Pool rapid channel types were identified as the sections of river which would sediment up first and could provide good indicators of river state. Although frequently discussed with KNP personnel, these findings were formally conveyed to KNPRRP members at the final WRC Steering Committee (June 1997) and KNPRRP PDMC meetings.

3. Studies on fish (Russell, 1997; Weeks et al 1996) and vegetation (Van Coller, 1993, Mackenzie 1998 Etc) have demonstrated the positive correlation between species distribution and diversity of the physical/geomorphic character of the rivers. Therefore a loss of bedrock from increased sediment storage in the rivers will mean a loss of structural and compositional diversity because many species are dependant on bedrock habitats. A loss of functional diversity will follow if it is not a direct consequence of the sediment accumulation.

4. We must recognise that the KNP objectives hierarchy was built and TPCs set on this information base. Limits were placed on the degree of bedrock loss and vegetation response (measured in terms of *Breonadia salicina* population structure) which would indicate that the desired state would not be met. It must be stressed that the TPC approach is designed to serve a Strategically Adaptive approach to management and is built on an "amber light" principle. The whole point is to be able to predict ahead of time when the system is "heading in the wrong direction" so that we can avoid the reactive management of the past, or that is the general result of other monitoring programmes. That is, most monitoring programmes tell one when it "has gone wrong" while TPCs and the modeling that goes with them, have better potential to tell us "it is going to go wrong". It is very important to recognize we should use TPCs in this way but in some cases it is too late.

5. Birkhead et al (in press) have modeled the physical response of the Sabie river to a range of hydrological and sediment input scenarios and predicted that provision of the Instream Flow Requirements for the Sabie River (Tharme et al 1996) would result in progressive long term sediment accumulation and thus a loss of bedrock influence. Although the full operating rules for the dam on the Marite river were not available at the time this report was completed, there is little doubt that the desired state of the Sabie River will not be met by the IFR. The Marite river contributes very little to the total Sabie run off. These findings were formally conveyed to KNPRRP members at the final WRC Steering Committee (October 1998) and KNPRRP PDMC meetings.

6. Mackenzie, van Coller and Rogers (1999) developed a model to predict *Breonadia* response to changing catchment conditions. This model predicts that the *Breonadia* TPC will also be exceeded under the sort of sediment accumulation scenario described by Birkhead et al. These findings were conveyed to KNPRRP members at the final WRC Steering Committee (March 1999) and KNPRRP PDMC meetings.

7. To digress awhile. We must note that in some ways this probably is the least of our short term worries in that we have already lost considerable biodiversity in the Levuvu *(Large scale loss of Fig* ***[a charismatic AND keystone species]*** *forests due to unnaturally severe*

drought. Any one thought about what the reaction would have been to losing this proportion of the Rhino ***[a charismatic but NOT keystone species]*** *population? Whole herds wiped out and the reproductive capacity severely curtailed because of major habitat change as a result of poor veld management. That is what it is equivalent to. Does the effort spent on Roan* ***[a charismatic but NOT keystone species]*** *match that spent on Figs? I would bet the drought knocked out a bigger proportion of the northern Fig population than TB has of the southern buffalo population).*

The Letaba is in a shocking state and does not meet the highest aquatic ecosystem objective, let alone the TPCs. *(There is probably more threat to KNP biodiversity from problems in the Letaba than from the whole of the rest of the park).* The Olifants is not much better. **Have we got a sense of proportion on this river issue yet? Have responses to date been in proportion to the severity of the problem or in proportion to the amount of scientific information flowing into the park?**

8. In May 1999 Freek Venter reported to the KNP Standing Committee on Conservation that Sabie River Bedrock and *Breonadia* TPCs would be exceeded. The following is his report on the meeting as e-mailed to KHR (Thanks Freek):

"No final decision has been taken. The Standing Committee decided that this item remains on the agenda so that continuous feedback can be attained, especially when James comes to demonstrate the model. The decision options put forward by me (with inputs from Harry Biggs) were discussed and the following were accepted: That the outcome of the remodeling of the hydrology (which will then include the megafloods) be awaited and that the TPC be revised in terms of the time-scale it is based on if necessary (e.g. that the 20 year time-scale the TPC is based on be changed to 30, 50 or 100 years. That more studies in the catchment should be conducted in order to shed more light on the subject and to facilitate the initiation of remedial action."

"Questions that need to be answered are:

1) Where is the main origin of the sediment (forestry firebreaks, rural areas or other) and how much sediment is coming from each source?

2) *Why is the river not capable of carrying the sediment through the system anymore? Is it because of increased sediment input, reduced runoff due to flood attenuation by forestry, reduced runoff by damming or reduced rainfall?*

3) *In case there is not a satisfactory management solution for the causes due to political or socio-economic realities in the catchment, what are the alternative options (discussions went around treating the effects e.g. the possibility of controlling reeds in the KNP to enhance sediment transport, the possibility of building the Madras Dam, etc.)*

It was also decided that the KNP should continue with its firm engagements with regard to the development and establishment of Catchment Management Agencies to ensure that integrated resource management is further encouraged."

9. It is important to understand that the above summarizes the situation and does not provide a critical assessment of the state of knowledge and rigour of the research and models. BUT, these are as good as ten years of peer reviewed, collaborative research and the resources at our disposal, have produced. You won't have got better in this country. The issue now is for KNP personnel to take appropriate action on a "best-available-data basis".

10. Kevin Rogers has been tasked by the KNPRRP to take this issue forward and "close the research/management/decision making loop" by precipitating a flow of information and decisions in response to the above information. His project has two facets:

(i) A theoretical component in which lessons learnt will be developed into one protocol to aid future decision making by the KNP and to aid implementation and institutionalization of Strategic Adaptive Management (SAM) process.
A very productive workshop was held in Pretoria in early May. It was attended by Antionette van Wyk, Harry Biggs (both KNP), Dirk Roux (CSIR River Health Programme) and Kevin Rogers (WITS/KNPRRP). Copies of the synthesis will go out separately. This theoretical component will only be of use in the longer term

to prevent us reinventing wheels. We need some action now.

(ii) A practical component in which the response of parties involved in decision making around this issue (KNP, KNPRRP, DWAF,etc.) is prompted in an adaptive management context.

This document and the issues in it are part of the practical component, and constitute part of the SAM process.

2.3.2 Notes from Discussions with Leo Braack, Willem Gertenbach and Danie Pienaar

This is a fairly random list of how I see the issues which were raised during informal discussions during May. They are for noting and digestion in the context of the above.

1. There must be explicit response from all affected parties (KNP research, KNP management, KNPRRP research and modelling, DWAF, River Health programme, should Mpumalanga parks be involved?) to the TPC notification.
2. This is a catchment problem that won't be solved by KNP alone. We must be ready to drop this in the lap of the new CMA when it is formed.
3. A big question is what can be done about the problem given that its origins are beyond the boundaries of the park? A bigger issue is that some appropriate action must be taken now as the problem might be long term but it won't go away and the sooner it is tackled the better.
4. Kevin will identify the flow path for information and decision making in KNP and DWAF and between the two. Thus far it appears that the KNPRRP informed Kruger researchers (Venter and Braack in KNPRRP meetings, Eckhart and Biggs at WRC steering committee meetings for the above projects) and Venter took the issue up at the Standing Committee meeting in May 1999. Where to now?
5. Must avoid simply deflecting the issue back to research for more info. This might be needed for very short term clarification but this is the result of 10 years of research. Yes there may be a need for even more research but this must not absolve parties (KNP, DWAF, etc.) of the duty to get some action in response.

6. If the real problem lies beyond the park boundaries how do KNP ensure that we don't end up with everyone else in the catchment blaming each other and avoiding the real issue.
7. The problem is one of sediment and water in the river channel but the sediment is generated from the landscape. DWAF/CMAs will only manage the river ecosystem. How will a CMA deal with the issue of unwanted sediment coming off the landscape?
8. What can be done within the park to manage the problem? Perhaps there is a continued role for river Forums which can integrate efforts to manage both river and landscape.
9. There was recognition that knowledge about rivers was not getting through to field rangers in Kruger. Thus when the subject was brought up at the St. Committee the significance of bedrock loss meant little to field staff. By contrast an issue such as a poached Rhino, of much less overall importance for biodiversity management, would have received immediate understanding and attention. This is a serious issue given that the KNPRRP has been going for 10 years and is about to come to an end. Field rangers need to be brought up to speed about rivers so that they can perform their rightful role in full park management.

2.3.3 So what and where to from here?

Having reflected on this for some time (the academics prerogative!) I would like to make the following points for discussion:

1. I believe we must understand that the KNPRRP has 6 months of life left. This means that we must enter a serious phase of rapid weaning the KNP off the KNPRRP. The umbilical cord has already been cut, its time for mother to force the intake of hard (to take?) foods!
2. Some implications of this are: i) There is no longer a body out there to which requests for more research/data etc. can be deflected. ii) All the data and models referred to above are in the hands of KNP personnel or available to them on the Internet. iii) The Mackenzie and van Coller model has now been formally transferred to KNP and staff instructed on its use. But note that this model is not the issue. It only precipitated it.
3. I believe that the Standing Committee should now engage KNP staff directly for the

information and solutions it needs. I believe answers are available to ALL its questions and there is no need to require more research as a first step. KNPRRP researchers are available to assist but should no longer be seen as the first line of defense.

4. A debate on who is to blame must be avoided at all costs. It will be acrimonious and unproductive. A very specific strategy must be developed to engage all stakeholders in the catchment to tackle the problem in a strategically adaptive manner. To *"continue with its firm engagements with regard to the development and establishment of Catchment Management Agencies."* is, in my humble opinion, not enough. A proactive and implemented strategy is required forthwith.
5. I think that a workshop to scope the problem and actions which can be taken in the short and medium term could help you. Participants would be KNP staff and KNPRRP researchers at least. DWAF personnel would have to be drawn in at some stage. NOTE: During the last week of July there will be a meeting in the park to further pursue the theoretical framework. DWAF personnel will be at that meeting. This could be a valuable opportunity and I urge the KNP to take the bull by the horns now.

Remember there is only 6 months before the cow abandons the calf!

2.4 KNP Managers' Response

Correspondence with KNP managers yielded responses in three spheres of interest:

The high **standard, relevancy and scientific rigour** were often hailed on different forums. The scale of the sediment problem, the socio-political nature and complexity thereof, and the uncertainty about the real origin of the sediment made it difficult for KNP management to get into top gear straight away. To know whether the sediment originated from the forestry areas or the rural settlements was quite important in the sense that to engage the forestry companies would be fairly straight forward, but to tackle the problem in the rural areas would have to involve our Social Ecology section and was much more sensitive and long term (more an education problem than immediate management). It was also noticed that streams originating in the KNP also carried huge amounts of sediments, which could lay the blame before the extreme droughts we had, or bad management practices in the KNP. All these scenarios would require very different remedial management actions. It was not merely a matter of asking for more info as if the available info was not of a high standard.

The **floods of February 2000** had a major influence on the unfolding (or lack thereof) of actions later on. The date of the 2nd TPC submission wrt the sediment problem is September 1999. So managers were geared up to make these things happen early in the following year .... and then came the floods. Some of the senior managers then firmly believed that the sediment problem was definitely solved (it was said that the TPC's were washed down the river towards Mozambique!) until the Crocodile farmers started moaning about sediment at their pump stations. No one worried about it for more than a year (water levels remained so high for the rest of the year that it was difficult to see whether this problem vanished or not). During this time the urgency for this TPC diminished as other priorities such as the financial crisis emerged and the urgency to get tourist facilities, roads and bridges fixed and start generating an income again. An important lesson in this is that new ideas, especially if they are fairly complicated, are not implemented automatically, especially in the face of many other pressing priorities. They need a lot of energy to make them happen.

Another factor that had a considerable influence on KNP management was the energy that went into **engaging the CMA business** at that stage. There were frequent meetings and the KNP was expected to attend all of them (as a consequence of their superior knowledge of river systems gained from the KNPRRP, of course!). KNP champions were nominated to represent the KNP on each of the Olifants, Sabie and Crocodile river CMC's. These had to be formal nominations signed by the Director. In the end Stefanie Freitag, Antionet van Wyk, Ralf Kalwa and Freek Venter were involved on a regular basis and rangers also attended some of the meetings. Apart from the usual bargaining for water rights, a spirit of co-operation often characterized these meetings (like the old days with the Sabie River Working Group and Olifants River Fórum), as well as a feeling of anticipation that drafting a CM Strategy would be a great and rewarding experience that could bind stakeholders together and tap into the KNPRRP knowledge bank to tackle many of the catchment problems. This was definitely not conducive to flying off to start one's own little separate group to promote, or worse even, to do catchment management on someone else's land. From the viewpoint of the KNP management, that the rivers were covered exceptionally well.

Chapter 3

Conceptual frameworks of science management interaction in environmental water management

3.1 Introduction

Interaction between scientists from the Centre for Water in the Environment (University of the Witwatersrand), River Health Programme (CSIR) and Kruger National Park led to three frameworks for science management interaction. These frameworks are all functional although they have been implemented to different degrees.

(1) The first frame work describes the operational system of Strategic Adaptive Management devised for, and implemented in, the Kruger National Park. This framework has become recognised internationally for its innovativeness and potential to deliver, in practice, current thinking on national park/large protected area management. It was first published in Freshwater Biology **41**:439-451.

(2) The second framework explains the challenges that Catchment Management Agencies will face when trying to manage river ecosystems in a sustainable and adaptive manner. This was published in Water SA (2000), **26** (4):505-511.

(3) The third framework is a description of the theoretical basis for Strategic Adaptive Management based on the experiences of the three authors [Rogers (Wits), Biggs (KNP) and Roux (CSIR)] and current thinking in the science of ecology and adaptive management theatres.

Summaries of the first two frameworks are presented below and full versions in Appendices.

3.2 Framework 1: Operationalising Strategic Adaptive Management in Kruger Park

In trying to operationalize the notion of sustainable ecosystem health/integrity ecologists have focussed on identifying sets of indicators which can be used to assess river condition relative to some normative, undegraded condition. Recognition and description of this normative state has proved illusive, particularly in highly variable semi-arid ecosystems. Without an operational definition of the desired system condition that reflects both scientific rigour and broader societal value systems, effective river management is unlikely.

Managing river health should not be confused with measuring it. Many monitoring or assessment programmes become ends in themselves rather than means to achieving specific management goals. The absence of a test of the results of monitoring further introduces the risk of management by observation and "pseudo-fact". Health "endpoints" provide a scientific description of management goals, while "values" provide a societal perspective. Together they complement the use of indicators and provide a strategic rather than reactive, approach to management.

The integration of value systems, endpoints and indicators of ecosystem health/integrity forms the cornerstone of a consultative management process for the rivers of the Kruger National Park.

An Objectives Hierarchy has been developed to service management's institutional hierarchy. A higher level "Vision" and Objectives serve upper levels of management with value based statements of strategic intent which have been tested against public opinion. Goals provide managers on the ground with specific ecological endpoints termed "Thresholds of Probable Concern" (TPCs). TPCs are described by a range of spatially and temporally bounded "criteria" which indicate system response to the main potential agents of change.

TPCs represent statements or hypotheses of limits of acceptable change in ecosystem structure, function and composition and thereby provide an inductive and strategic approach to adaptive management in a data poor situation. Integrated monitoring, research and modelling track criteria relative to TPCs and question whether management action, or recalibration of the TPC, is needed. TPCs thus provide direction for management but their validity and appropriateness are frequently challenged and adaptively modified.

The Objectives Hierarchy mandates Kruger Park management to "....maintain biodiversity in all its natural facets and fluxes...". Alluviation, as a consequence of increased sediment supply and decreased sediment transport capacity, is a major threat to biodiversity of the bedrock controlled rivers which flow through the park. Thus, for example, TPCs for geomorphic diversity reflect permissible ranges of change in bedrock character of the physical template, measured as change in the proportion of different geomorphic units in identified representative reaches. TPCs for riparian vegetation, measured as change in population structure of selected species within the representative reaches, reflect a likely range of biotic response to change in the physical template. A specific set of criteria, reflecting response to the major agents of change, therefore provides a parsimonious programme to assess ecosystem condition relative to stated goals.

More detail is provided in Appendix 1.

3.3 Framework 2: Challenges for operationalising SAM in catchment management agencies

Catchment management agencies (CMAs) have no tested precedent in South Africa and will have to evolve in complex and changing business, social and natural environments as they strive to ensure that equity and social justice are achieved within ecological limits. Traditionally, very different styles of management have been used for resource exploitation and resource protection and this will present a serious dilemma for CMAs.

As the human population has grown and natural resources have declined, there has been increased effort to control nature in order to harvest its products and reduce its threats. Initially such "command and control" management has been successful as agencies prosper on short-term gains. However, when natural variation is reduced the ecosystem loses its resilience and ability to "bounce back" from disturbances. There are a number of lessons we can learn from past experiences in government bureaucracies, natural resource management and business.

The first lesson is that the longer term consequence of command-and-control management is always either a reduction or cessation of resource supply.

The second lesson comes from adaptive resource management (ARM).ARM acknowledges that, because nature is in a continual state of flux and our understanding of ecosystem functioning is poor, a fundamental problem for decision makers is that they must deal with uncertainty from an imperfect knowledge base. A learning-by-doing approach becomes a prerequisite for effective management. Unfortunately, there has been a tendency to superimpose adaptive management on bureaucratic institutional structures. Such flouting of the fundamental management axiom "form must follow function", has thwarted many attempts at adaptive management. This provides our third lesson.

Recognition that authoritarian, command and control, bureaucracies respond too slowly to survive in changing environments has led managers in government, industry and businesses to create "learning institutions" which combine adaptive operations and generative leadership (lesson four). Effective knowledge management is seen as a critical success factor in turning command-and-control management into adaptive, learn-by-doing management (lesson five).

CMAs which recognize the dangers of excessive command and control, the need to integrate stakeholder values and activities, and the potential of an adaptive and generative management approach, will need to structure their activities carefully.

At present there is much focus on the structure of CMAs and much less on how they should function. Form is preceding function in many instances. When function is discussed it centers on how regulatory mechanisms and permit systems will keep resource use under control. The concern is seldom with how the ecosystem will be managed. This sort of thinking could lead to a classic command-and-control management approach if not tempered with a more adaptive process.

Strategic adaptive management (SAM) is a local derivative of ARM designed to generate consensus management which is inclusive, strategic, adaptive and creative. SAM is a process in which effective knowledge management is central to building a partnership between science, management and society to achieve a common vision. It has considerable potential for application to CMAs.

More detail is provided in Appendix 2.

3.4 Framework 3: General principles and process of SAM

This "theory" or "philosophy" of SAM has been kept as short and concise as possible in the hope that it will be read and absorbed. It has not been expanded in an appendix. It will mean little if read in isolation from the preceding two sections which are expanded in Appendices 1 and 2 respectively.

A SAM Philosophy

Definition: *SAM is a process of managed learning which steers strategic action to achieve desired ecosystem end points. It hinges on the axiom that ecosystems are "complex dynamic systems".*

A functional SAM operation has three components: **Research** steered by integrators, **Interfacing** steered by networkers, and an **institutional system** steered by generative leaders.

Research approach to complex dynamic systems

- Multi-scaled (hierarchical in space and time) studies, interdisciplinarity and a social contract are practiced not preached.
- All 3 "tools" of research (Pickett et al. 199? "Ecological Understanding: the theory of nature and nature of theory") are used to relate "observable phenomena" to "conceptual construct". The 3 tools are: generalisation (pattern seeking), causal explanation (quantification of relationships) and testing. Testing may be by either confirmation or falsification. Observable phenomena may be natural or managed components of the ecosystem.
- A "conceptual construct" of the role of key agents of change in ecosystem dynamics provides strategic direction.
- Co-design of research projects by scientists and agency integrators leads to mutual benefit. Most projects have to be thesis-able because most research is conducted by post-graduate students.

Interfacing philosophy

- Research is mostly conducted by academic institutions but it is treated as an extension arm of the agency which operates as a virtual enterprise.
- All action (management) activities are judged by the learning opportunities they provide
- Aligning science and management mental models/conceptual constructs is central to developing vision for management and translating this into desired ecosystem end points.
- A pragmatic interface is built between science and management on a best-available-data, more-with-less and achievable-under-resource-constraints, mind set.
- The use of indicators (of system response to agents of change) and TPCs to monitor and audit system state, requires a close working relationship between scientists and managers.

Institutional system design

- Three cornerstone activities drive SAM: Strategic knowledge management, Operations and Decision making. The virtual institution (organisation and outside researchers) must be designed to emphasise these. (See Fig. XX Appendix 2)

- No one individual operates entirely in any one sphere and therefore their job descriptions place them somewhere on each of the three axes.
- Operations is further divided into Research (internal), monitoring and logistical support. (In Kruger logistical support can be further divided into tourism, technical services and rangers)
- Most new knowledge is derived from academic researchers operating outside this system hence the importance of explicit the interfacing processes.

Note: The process of changing complex hierarchically structured bureaucracy into a functional adaptive organisation which uses SAM as its central operating process is termed "institutionalisation". This is dealt with in more detail in Appendix 2.

Ensuring science is used in management and vice versa is the essence of SAM. It is based on four premises:

1. Good, multi-scaled science under a paradigm of ecosystem flux.

Research must be directed at assessing and understanding change in ecosystem state and the agents of that change. The "conceptual construct" which the research is testing has ecosystem (management) goals explicitly embedded in it, to provide catalysts for project planning by scientists.

2. A science/management partnership based on shared vision, needs, values, ecosystem end points and reward system.

The partnership operates by facilitating a learning-by-doing process during which there is co-evolution of vision, needs, values, goals and reward system. The process is explicitly aimed at generating the co-operative action of scientists and managers which provides the mechanism for testing the conceptual construct of ecosystem structure, function and the defined end points.

3. Defined behaviour of the implementing insitution.

This is the "Management insitution" because most often science, appropriately, operates outside of the implementing agency. Appropriate institutional "behaviour" embodies a "learning" culture built around a central core of strategic knowledge management. This is achieved by generative leadership (designer, teacher, steward) which creates a culture of shared purpose and institutional learning.

4. Appropriate individual behaviour

We must recognize that "we" do have a problem because science is not well enough used in policy and management. If this is accepted then we must change our behviour to achieve the ends described above. This requires extraordinary personal commitment and understanding of the role one can/must personally play to effect change.

The most important lesson to learn is the need to act on available knowledge in an adaptive manner. Decisions made must be seen as hypotheses which the learning individual/institution will challenge, under guidance of the vision, as knowledge grows.

While leaders must adopt the generative role described above, the main change for other individuals should be from viewing uncertainty, complexity and change as threats to treating them as opportunities for learning and improving.

5. Some DON'T'S

Don't focus on predefined products but on process and outcome

Don't focus on predefined procedure but on process and out come

Don't try to transfer research findings directly. Transform them into technology first.

Don't transfer technology to the user organisation but diffuse it into the organisational system

Don't complain about too little money/too few resources or people/not enough information. Use what you have to formulate some hypotheses that can be tested in an adaptive management process.

Similarly the challenge to scientists who disagree is to turn their disagreement into hypotheses which form the basis of learning by doing. If they don't the process stagnates.

Chapter 4

Lessons for future technology transfer/resource management projects

Key elements of an analysis of how things need to be improved in Kruger May 1999

1. There is a dilemma of "event" verses "strategic" responses to problems in conservation and resource management. Strategic responses are poorly developed and a hindrance to SAM. There should automatically be BOTH event and strategic responses to every problem. In fact it should go further and recognize that there will be a range of types of response e.g. action response, strategic, political, bureaucratic each with different time horizons. Consequently water resource management personnel need very explicit "Response Guidance" which is formally built into organizational structure and function.

2. On the other hand there are generally good data and knowledge capture from monitoring (a strategic operation) and poor data capture from events. There is a need to capture the wisdom from reporting of events and incorporate it appropriately into organisational knowledge management structures.

3. In most adaptive management programmes, including that Kruger, a lot of guidance is provided for "problem solving" but much less for "action taking" at the implementation phase. This is because problem solving is more generalisable. Resource management organisations need to make the "action taking" guidance more explicit and ensure its linkage to strategic plans.

4. Furthermore, there is a need to entrench goal orientation in response guidance, especially as means to testing hypotheses. Goals are the essence of strategic management. An iterative process of auditing goals and reflection must become habit.

5. There is a need for more explicit understanding of how to make resource management

organisations , learning organisations. How do people become automatic learners and how do leaders become more generative in their approach?

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Appendix 1

Integrating indicators, endpoints and value systems in strategic management of the rivers of the Kruger National Park South Africa

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K. Rogers* and H. Biggs#

* Centre for Water in the Environment, University of the Witwatersrand, Johannesburg

Kruger National Park, Skukuza, South Africa

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SUMMARY

1. In trying to operationalize the notion of sustainable ecosystem health ecologists have focussed on identifying sets of indicators which can be used to assess river condition relative to some normative, undegraded condition. Recognition and description of this normative state has proved illusive, particularly in highly variable semi-arid ecosystems. Without an operational definition of the desired system condition that reflects both scientific rigour and broader societal value systems, effective river management is unlikely.

2. Managing river health should not be confused with measuring it. Many monitoring or assessment programmes become ends in themselves rather than means to achieving specific management goals. The absence of a test of the results of monitoring further introduces the risk of management by observation and "pseudo-fact". Health "endpoints" provide a scientific description of management goals, while "values" provide a societal perspective. Together they

complement the use of indicators and provide a strategic rather than reactive, approach to management.

3. The integration of value systems, endpoints and indicators of ecosystem health/integrity forms the cornerstone of a consultative management process for the rivers of the Kruger National Park.

4. An Objectives Hierarchy has been developed to service management's institutional hierarchy. A higher level "Vision" and Objectives serve upper levels of management with value based statements of strategic intent which have been tested against public opinion. Goals provide managers on the ground with specific ecological endpoints termed "Thresholds of Probable Concern" (TPCs). TPCs are described by a range of spatially and temporally bounded "criteria" which indicate system response to the main potential agents of change.

5. TPCs represent statements or hypotheses of limits of acceptable change in ecosystem structure, function and composition and thereby provide an inductive and strategic approach to adaptive management in a data poor situation. Integrated monitoring, research and modelling track criteria relative to TPCs and question whether management action, or recalibration of the TPC, is needed. TPCs thus provide direction for management but their validity and appropriateness are frequently challenged and adaptively modified.

6. The Objectives Hierarchy mandates Kruger Park management to "....maintain biodiversity in all its natural facets and fluxes...". Alluviation, as a consequence of increased sediment supply and decreased sediment transport capacity, is a major threat to biodiversity of the bedrock controlled rivers which flow through the park. Thus, for example, TPCs for geomorphic diversity reflect permissible ranges of change in bedrock character of the physical template, measured as change in the proportion of different geomorphic units in identified representative reaches. TPCs for riparian vegetation, measured as change in population structure of selected species within the representative reaches, reflect a likely range of biotic response to change in the physical template. A specific set of criteria, reflecting response to the major agents of change, therefore provides a

parsimonious programme to assess ecosystem condition relative to stated goals.

INTRODUCTION

In trying to operationalize the concept of sustainable ecosystem health or integrity ecologists and managers have focussed on identifying sets of indicators which are used in assessing river condition relative to some normative, undegraded reference condition. Much less thought seems to have been given to how indicators, reference sites and repeated assessment (monitoring), integrate into comprehensive river management plans. As a consequence many assessment programmes are criticised for being short on scientific rigour and becoming ends in themselves, rather than means to achieving specific management goals which reflect societal value systems.

In this paper we initially explore the links between science and management, with particular reference to the role of assessment/monitoring programmes, with the purpose of identifying essential elements for operationalizing the concept of sustained ecosystem health/integrity. In the second part of the paper we describe how indicators, end points (goals) and societal values are integrated into the assessment of ecosystem health/integrity as part of the overall management plan for the rivers flowing through the Kruger National Park, South Africa.

The debate about whether health or integrity is the overall target for management is distracting to the purpose of this paper. Karr (1996) distinguishes between the two by reserving integrity for the more natural ecological systems and health for conditions desired by humans but not necessarily natural. The debate is confounding in our situation where we are dealing with a natural protected area but anthropogenic influences in river catchments upstream of the park borders have degraded some rivers, or sections of rivers, to a state where human definitions of the desired future state must govern rehabilitation (Breen, Quinn and Mander, 1997). While accepting the validity of Karr's arguments it is better to recognise that both concepts apply in our case, although the needs for assessing ecosystem integrity probably dominate and thereby influence the approach taken to manage river ecosystems.

INTERACTION BETWEEN SCIENCE AND MANAGEMENT AND THE ROLE OF ASSESSMENT PROGRAMMES

Much of the debate around the effective interaction between science and management in conservation and resource utilisation has centred around the concept of adaptive management (Holling, 1978; Walters,1986; Romesburg, 1981; Nudds and Morrison, 1991). The essence of adaptive management is that it treats management actions as potential learning opportunities that can feed back more reliable information to improve decision making (Lancia, Nudds and Morrison, 1993). A process of "management by experiment" has been proposed (Romesburg, 1981) but few conservation agencies have succeeded in operationalizing the concept (Walters, 1997).

In large measure this can be attributed to the fact that scientists and managers traditionally adopt very different operating procedures (Cullen, 1990; Rogers, 1997) which to most appear incompatible. Incompatibility is however probably more a function of the fact that few individuals, or even small groups, can effectively operate under two paradigms in one job. The emphasis should then be focussed on interfacing these two fields of endeavour, with monitoring and assessment programmes playing an important role in this process.

Effective interaction between science and management is best achieved when the respective procedures and roles in the overall process of gaining and using knowledge, are clearly identified (Rogers, 1997; Fig. 1). This provides an opportunity to highlight the points at which effective interaction can be achieved and those where conflict or incompatibility are likely to occur.

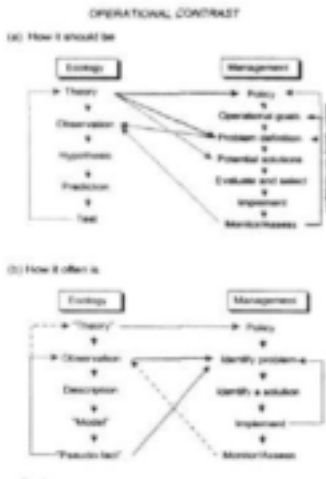

Figure 1. An operational contrast between the science of ecology and the process of environmental management. (Modified from Rogers, 1997)

Good science, a prerequisite for reliable information (Nudds and Morrison, 1991), and good management follow distinct processes. It is the way they interface which is provides the basis for scientific management and useful ecology (Rogers, 1997). In this interaction science must follow a hypothetico-deductive approach of hypothesis testing under an umbrella of established theory (Fig. 1a). Management, on the other hand, generally operates under the umbrella of a policy mandate which must be translated into operational goals (Christensen, 1997; Rogers, 1997). Most management activity should then revolve around solving problems which prevent these goals being achieved, and around careful evaluation of a range of possible solutions which might reduce the risk of inappropriate action.

Good management always incorporates a monitoring or assessment programme (Noss, 1990; Chistensen, 1997) which would; a) provide a cross-check on the accuracy of the problem definition and appropriateness of the selected solution, b) audit goal achievement, and c) on a longer time scale, feed back to the evaluation of policy (Fig. 1a). Feedback from management's efforts to improve the scientific observation base is essential to effective interaction. Similarly feed-on from science, to improve the policy framework and management's ability to define problems, generates a healthy interactive environment for science and management.

In our experience science and management, especially in the fields of environmental biology and conservation, seldom formalize these operational rules. We have noted many variations on the theme described above but a general pattern emerges (Fig. 1b) in which science loses the hypothesis testing approach and becomes too descriptive with a focus on producing models, usually informal mental models, which are seldom explicitly tested . The consequence is that a body of "pseudo-fact" (Holling 1997) is generated in a self-reinforcing operational mode which seldom challenges theory. This problem is exacerbated in southern hemisphere semi-arid areas when theory derived from northern-temperate studies is used as the platform from which to interpret observations and define management problems (Williams, 1988).

Such an uncritical approach to science feeds over into management, leading to problems being poorly defined and solutions being too rapidly and uncritically accepted, without being evaluated against a set of goals which define the desired outcome of the policy framework. In many instances monitoring programmes are not explicitly set up to monitor the consequences of management actions but rather to assess, by means of indicators, the "state" of the system. In either case however monitoring results are put to limited use other than to identify the next "problem", real or pseudo. As a consequence, because it lacks direction, purpose and a defendable scientific base, management becomes highly reactive to the never ending array of surprises nature, economic forces and social adjustments place on its door step.

The fundamental difference between these two models of science/management interaction are that, in the second model (Fig. 1b), science lacks an explicit test of its findings and management lacks an explicit translation of policy into achievable and scientifically defendable operational goals and a defined auditing process. Management actions are therefore not effectively tested against societal value systems or scientific understanding and management lacks direction, purpose and transparency.

A major problem with integrating science and management has been the lack of established theory of, and formal procedure in, ecosystem management (Christensen, 1997; Meyer, 1997). It has not been easy for scientists and managers to explicitly identify nodes for and processes of, interaction.

Management of the Kruger National Park, prior to the nineteen nineties, had many overtones of this second flawed model but it now explicitly seeks to avoid these pitfalls by becoming transparent and strategically adaptive (Rogers and Bestbier, 1997). Three interlinked and parallel processes were set in motion to achieve this:

1. The first was to define an inclusive and iterative management process which involved stakeholders and provided a clear role for monitoring of ecosystem conditions.

2. The second was to define the overall purpose of management and set an acceptable desired state (goals/end points) in operational terms.

3. The third process was to integrate hypothesis generation and testing into the science/management partnership which audits goal attainment.

The overall accomplishment, for the purpose of this paper, was a structured assessment programme, integrated into transparent management for river health/integrity.

THE MANAGEMENT PROCESS

The strategy has been to develop a consultative management process in which interactions between stakeholders, managers and research are facilitated by a Decision Support System (DSS) (Breen, Quinn and Deacon, 1995). The process consists of three subsets of activities (Fig. 2):

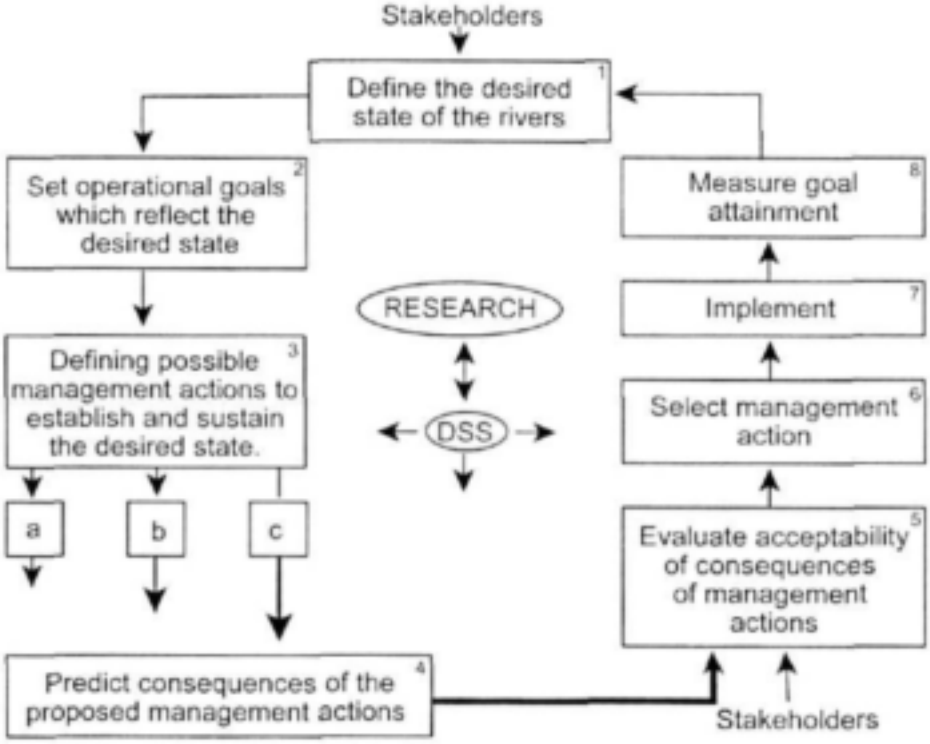

Figure 2. The consultative process used for the management of the rivers flowing through the Kruger National Park can be divided into three subsets of activities; Operations (boxes 2,3,6,7), Predictive (boxes 4 & 6) and Monitoring/Auditing (boxes 1 &8).

1. An Operational Framework with two functions: (1) To set and evaluate attainable and acceptable goals which reflect the desired future state for the rivers. Attainability must be judged on the basis of ecologically realistic targets and the operational capabilities of management. Acceptable goals will meet the various stakeholders broad aims. (2) To select and implement appropriate management actions.

2. A Predictive Modelling Framework for prediction of the consequences of management actions and of system change in general aids in evaluating the acceptability of the consequences of management actions.

3. A System Response Framework for monitoring system response to management actions and natural disturbance/change, and auditing goal (desired state) attainment.

The DSS is essentially a toolbox (MacKay, 1994) which provides, operates and maintains a range tools (techniques, protocols, models, procedures) for servicing the interactive management process. This is the technological interface between management and research.

Research is the process which generates data and understanding needed to produce tools for the DSS. As data and understanding are improved so too is the ability of the DSS to service the management process.

The initial challenge of this management/research partnership was to describe the desired future conditions of the river in pragmatic terms. It was essential that this description could be translated into achievable operational goals, be compatible with the predictive potential developed by researchers and be measurable in the field, given the resource constraints of management. It would serve little purpose to set a "desired state" in detail so fine that it could not be motivated to stakeholders, was beyond predictive capabilities and was too costly to achieve and audit.

DEFINING AN ACCEPTABLE DESIRED STATE IN OPERATIONAL TERMS

The concept of a "desired state" (also referred to as "desired future state/condition" or "desired trajectory") has had many independent origins all over the world and is generally used to indicate the need for some foresight and commitment from policy makers and managers as to the condition in which an ecological system should be maintained. As such it is used as a euphemism for operational goals (Christensen, 1997).

To some the desired state may be represented by scientifically identified end points, while to others it may be represented by human values. Without an operational definition of the desired end point, effective management is unlikely (Costanza, 1992) and without broad consensus on that definition, acceptance within wider societal value systems is equally unlikely.

Our approach to defining the desired state was to develop an objectives hierarchy (Fig. 3; Rogers and Bestbier, 1997) which could service an institutional hierarchy with acceptable and achievable operational goals, and map out a credible future (endpoint; Costanza, 1992) for the river ecosystems. A future which reflected both societal value systems and scientific rigour.

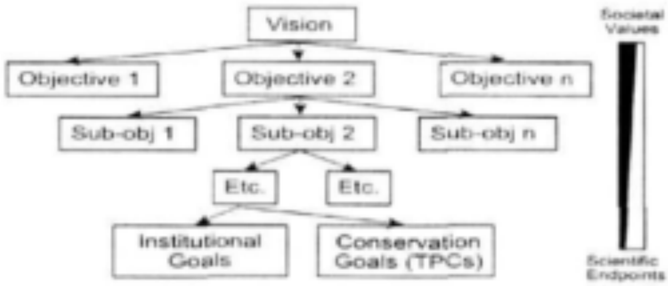

Figure 3. The essential structure of an objectives hierarchy which incorporates societal values and scientific end points into the description of a "desired state" for ecosystem management.

The hierarchy begins at the broadest level with the organisation's "vision" for management. The vision is a philosophical statement of intent which describes the core business of the organisation and is durable beyond changes in personnel and organisational structure. It is synonymous with terms such as "mission statement" or "strategic objective" (Keeney, 1992) and while scientifically acceptable, it largely reflects the societal values embedded in broad policy. It is therefore the sort of statement which chief executive officers use in their dealings with the press or politicians and is readily understood by all stakeholders.

It is not enough to provide a broad vision and expect everyone to know what to do, or to expect scientists to feel comfortable with its lack of detail and potential scientific ambiguities. The vision is therefore decomposed into a hierarchical series of objectives of increasing focus, rigour and achievability. Objectives are qualitative articulations of values defined in the vision and operating principles of the organisation. They form a foundation on which to develop quantitative, operational goals.

The finest level of the hierarchy is defined by such goals. We define a goal as "an achievable, testable and auditable target with specified spatial, temporal and confidence limits". These goals may be either "institutional" or "conservation" goals. Institutional goals define achievable targets for managing institutional structures and processes, and, while fundamental to defining the resources available to management, are not of concern to this paper. Conservation goals define end points for ecosystem management and must thus be scientifically rigorous without compromising the value systems embodied in the vision.

The process of structuring an objectives hierarchy results in a deeper, more accurate understanding of what is important in the decision context (Rickhow, 1994) and in our case-study is explicitly structured to integrate value systems and scientific principles.

The higher level vision and objectives therefore serve stakeholders, and upper levels of management, with statements of strategic intent. Low level goals, on the other hand provide managers on the ground with scientifically rigorous, spatially and temporally bounded targets of ecosystem condition compatible with the vision. These targets are termed Thresholds of Probable Concern (TPC) and act as amber lights to warn managers of possible unacceptable environmental change. TPCs form the basis of the monitoring programme and the link between management targets and an hypothesis testing approach to science.

THE DEVELOPMENT, USE AND AUDITING OF TPCs

Thresholds of Probable Concern are upper and lower levels of change in selected biotic and abiotic variables which act as indicators of the acceptability of ecosystem condition. The development, use and auditing of TPCs must be integrated with research and management processes to ensure that the validity of TPCs is continuously tested, they are based on current information and they are used to ensure that management is strategically adaptive, rather than reactive. The science/management partnership in the Kruger National Park has developed an iterative process to ensure that research, predictive modelling and operations interact with monitoring of system response in the developing, testing and auditing of TPCs (Fig. 4).

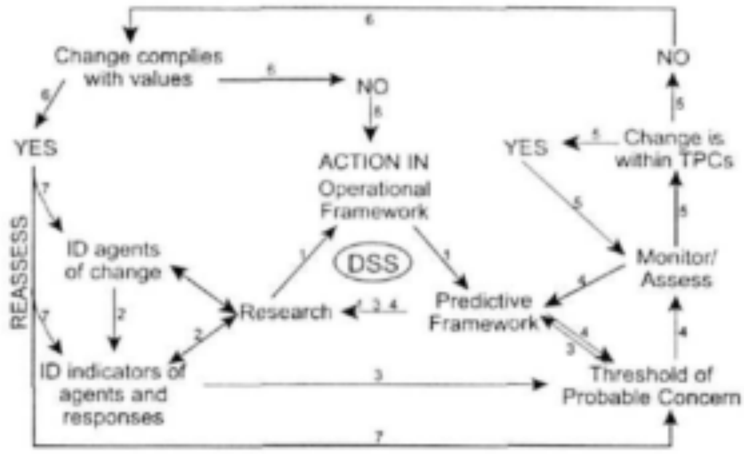

Figure 4. The iterative process whereby Research, Prediction and Operations interact with Monitoring of System Response to develop, test and audit Thresholds of Probable Concern. The numbers on the arrows define the sequence in which steps are taken.

Research in the Park is focussed on identifying the main agents, natural and anthropogenic, of change in river characteristics, and on identifying indicators of these agents and of system response to them (Fig. 4). The collective wisdom of science and management, guided by the objectives hierarchy, is then used to define, in spatial and temporal terms, the upper and lower levels of these indicators which will lead to concern about the degree of ecosystem change. These levels are the Thresholds of Probable Concern.

TPCs represent scientifically described endpoints for ecosystem management and form the basis of an inductive approach to adaptive management as they are invariably hypotheses of limits of acceptable change in ecosystem structure, composition and function. As such, their validity and appropriateness are always open to challenge and they must be adaptively modified as understanding and experience of the systems being managed increases.

A structured monitoring programme assesses change in these indicators and data are fed back into models in the predictive framework. When a change in ecosystem condition is measured, or preferably when modelling predicts it will occur, this prompts an assessment of the causes of change and whether or not it falls within the TPC (Fig. 4). If it does, monitoring continues but if it falls beyond the TPC, the cause, degree and nature of change is assessed relative to the values embodied in the higher level objectives and vision statement. If the change is compatible with these values, for example it was caused by a natural flood, the information is fed back to researchers who would use it in their experiments and models to test the validity of the TPCs. If it is not compatible appropriate action must be taken within the operational framework (Fig. 2) to address the cause of change. Thus the TPC concept is used to guide research and model development, to assess change in ecosystem condition and to prompt appropriate management action.

AN OBJECTIVES HIERARCHY FOR THE KRUGER PARK RIVERS

Management of terrestrial and aquatic ecosystems of the Kruger Park is integrated under one objectives hierarchy. The vision mandates managers to "maintain biodiversity (*sensu* Noss 1990) in all its natural facets and fluxes and to provide human benefits, in keeping with the mission of the National Parks Board, in a manner which detracts as little as possible from the wilderness qualities of the Kruger National Park" (Braack, 1997). The comprehensive decomposition of this hierarchy is beyond the scope of this paper but an abridged version (Fig. 5) illustrates the relationship of river management objectives to those of other ecosystems and presents paraphrased versions of subsidiary objectives.

The objectives hierarchy as a whole represents the desired state for the Kruger Park rivers and incorporates a range of management values set after wide consultation with interested and affected parties. Important components of the hierarchy with respect to this paper are:

1. A Public Relations programme promotes and audits societal values embodied in the hierarchy.

2. The role of research in the Park is primarily to understand and predict biodiversity flux and to service and test TPCs.
3. The role of personnel within the auditing section is to establish, through monitoring, the long term flux in structural, composition and functional biodiversity and, develop and audit the TPCs.

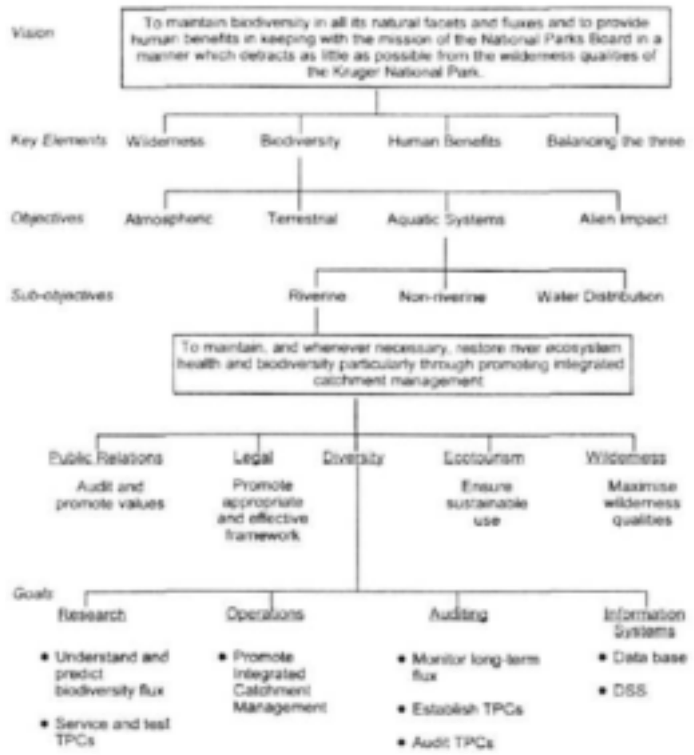

Figure 5. A simplified and abbreviated version of the objectives hierarchy for management of the rivers flowing through the Kruger National Park. (Modified from Rogers and Bestbier, 1997)

KRUGER PARK RIVERS MONITORING PROGRAMME: AGENTS OF CHANGE, INDICATORS AND TPCs

The research/management partnership in the Kruger National Park has identified two primary sets of agents of change in the five perennial rivers which run through the park. The first is an array of catchment activities affecting water quality which differ from river to river. The second is increased sediment storage in the rivers resulting from increasing sediment supply from poorly managed catchments, and decreasing sediment transport capacity as a consequence of reduced flows (Heritage et al., 1997a). This will have particularly serious consequences in most rivers as it is the mixed bedrock/alluvial nature of the river beds which generates a high habitat and species diversity. Alluviation as a consequence of increased sediment storage will reduce bedrock influence and homogenize the system.

The objectives hierarchy for management of the rivers is based on the multi-scaled, multiple levels of organisation, perspective of biodiversity proposed by Noss (1990). It thus mandates management to set TPCs and identify indicators of change in structural, functional and compositional diversity at a range of scales and levels of organisation for each of the rivers. Workshops, involving all the local expertise that could be mustered, were used to set TPCs and identify indicators and the spatio-temporal scales of measurement (Rogers and Bestbier, 1997). Delegates were charged with defining TPCs and proposing the most parsimonious monitoring programme possible, on a best available data (much of it unpublished) basis. Thus, TPCs have been set for fluvial geomorphology, vegetation, fish communities, invertebrates, avifauna, the role of the riparian corridor as an altitudinal migration route into the catchments, water quality and flow regime. The result is a series of hypotheses of the limits of acceptable change which have been set using the full extent of the present knowledge base and they have been integrated into an adaptive management programme.

It is beyond the scope of this paper to deal with all the TPCs for all 5 perennial rivers. Details can be found in Rogers and Bestbier (1997). The indicators and TPCs for geomorphology and riparian vegetation in the Sabie River are used as examples here.

The Sabie River

The primary problem facing managers and scientists on the Sabie River has been to predict and monitor the response of biodiversity, in specific river sections, to modifications in hydrology, sediment supply and water quality originating at the catchment scale. Any attempt to understand, let alone predict, the causal links between catchment processes and downstream biotic response is fraught with problems of scale, feedback and contingency interactions. The pragmatic approach has been to focus attention on the downstream consequences of change in flow and sediment on the contemporary geomorphological template and to assess biotic response to geomorphic change (Rogers, 1997).

The Sabie River flows over a relatively young erosion surface which resulted from the westerly retreat of the Great Escarpment after the break-up of Gondwanaland. Two major cycles of rejuvenation resulted in a slow lowering of the land surface which enabled the river to cut into resistant rock formations without major directional change. Consequently, the Sabie River is confined to a narrow shallow valley within existing host rock. Active channel evolution and sedimentation are restricted within this zone, which is termed the macro-channel (Heritage et al., 1997a). Thus, the river is controlled by the underlying geological structure and bedrock lithologies but, with high sediment inputs and moderate slope, it also displays some alluvial characteristics within the macro-channel. The mixed bedrock/alluvial nature of the river provides a very high instream and riparian habitat diversity much prized by conservationists.

A hierarchical classification of the river (Heritage et al., 1997b; Pickett and Rogers, 1997) provides the main basis for dealing with scale problems. At the coarsest scale there are five perennial and a number of ephemeral river catchments, resolvable at scales of hundreds of square kilometres. At the next level a single river such as the Sabie, appears on a linear scale of +100 km and can be divided along its length into zones (40-100 km) based on hydrology and sediment yield. Within the Kruger Park the zones are subdivided into macro-reaches (5-20 km) defined by specific geology, stream gradient and broad vegetation type. A macro-reach does not repeat. In contrast, a reach occupies the 10km - 100m scale and contains one or more channels types defined by channel geomorphology. There are five generic channel types (alluvial single thread, alluvial braided, mixed alluvial/bedrock anastomosing, bedrock anastomosing, mixed pool-rapid) with some sub-divisions to give a total of nine channel types. The reach is the main kind of mosaic to repeat within the river. Its repeating sub-units are geomorphic units (e.g. bedrock pool, bedrock pavement, riffle, braid bar, point bar etc.) at scales of 10 - 100m. The smallest scale is the micro-site (0.1 - 10m) defined by micro-topography, substratum type and elevation on the geomorphic unit.

The broad strategy of research and management has been to accept, at least initially, that if management can achieve a specified spatial and temporal range of bedrock and alluvial conditions in the contemporary geomorphic template, biotic diversity will be catered for in this large protected area. The overall management objectives and TPCs are thus defined by the structure of different types of river reach, with particular reference to the relative contributions of bedrock and alluvial features. Reaches are described on the basis of the proportions of different morphologic units, and different reach types are distinguished by differential proportions of these units. Management is aided by the designation and description of a few site specific reaches as "Representative Reaches" which form the focus of monitoring activities.

Auditing geomorphological response on the Sabie River

A combination of what are termed criteria (the measured object or process) of measurement, units of measurement and scales of measurement were used to define the geomorphological indicators of ecosystem response to the main agents of change (Table 1). Geomorphology represents a structural component of biodiversity at the river landscape scale. The geomorphic criteria selected were the five (of the total of 9) channel types characterised by bedrock influence. The units to be measured within these are the four (of 23) bedrock geomorphic units which have been shown to be susceptible to sedimentation (Heritage et al., 1997a). These criteria are monitored by mapping change on aerial photographs every five years and after droughts or floods of greater than 1 in 25 years return period, in representative reaches only. In this way monitoring can fill the dual function of auditing system response and establishing system variability.

Table 1. Monitoring the geomorphological (structural, landscape) compenent of biodiveristy of the Sabie River.

Agents of change and rationale: Increasing sediment supply and decreased sediment transport capacity will result in increased sediment storage, alluviation and loss of diversity of bedrock influence.

Measurement Criteria	Measurement Units	Measurement Scale	Thresholds of probable concern (TPC)
Selected channel types (5 of 9) in designated representative reaches:	Area of selected geomorphic units (4 of 14) on aerial photographs:	Temporal Every five years and events (floods, droughts)greater than 1 in 25 year return interval	Directional loss of bedrock influence and water surface area at winter low flow (20 yr prediction).
Bedrock anastomosing	Bedrock core bar	Spatial 10^2 - 10^3 m per representative reach 20X20m grid square	Anastomosing channel types: Bedrock core bars 50% cover or more. Other units three units must be 2-10% of total area.
Alluvial anastomosing	Anastomosing bar		Pool-rapid channel types: lateral and point bars ≥ 20% and pools ≥15% of total area.
Mixed anastomosing	Bedrock pavement		
Bedrock pool rapid			
Mixed pool rapid	Bedrock pool		

Change in the influence of bedrock on channel characteristics has been used to set the lower limits of TPCs. At the scale of the Sabie River within the Kruger Park (essentially the zone scale) the TPC would be reached if the indicators showed a directional loss of bedrock area, at winter low flow, over a prediction period of 20 yrs. Previous studies (Carter and Rogers, 1995) have shown it is unlikely that directionality of change can be described as established for time scales less than twenty years. A change over 20 years would demonstrate that characteristics of the main agent of change had exceeded natural variation. Upper TPC limits are related to the converse increase in the proportions of alluvial features but to measure these would be superfluous.

At finer detail, bedrock core bars should represent a cover of 50% or more in representative reaches of the anastomosing channel types, while in the two pool/rapid channel types, lateral and point bars should be no more than 20% cover and pools no less than 15%. The pool/rapid characteristics providing the upper limits of the TPC in terms of alluvial features.

The example demonstrates that, in terms of the process of developing, auditing and using TPCs illustrated in Fig. 4, geomorphological research has defined both the main agent of change (sediment storage) and the key indicators of response (bedrock influence and proportions of bedrock characterised geomorphic units). Quantification of upper and lower limits of acceptable change in these indicators provides TPCs which are monitored by aerial photographic analysis at specific spatial and temporal scales. A rule based model (Moon et al., 1997) provides the basis for prediction of channel response to catchment level changes in hydrology and sediment supply. A 50 year aerial photographic record provides a historical record against which to evaluate projections of future change.

Auditing vegetation response to geomorphic change

The main premise behind vegetation TPCs (Table 2) is that alluviation will reduce the diversity of regeneration niches and flow reduction will result in the encroachment of terrestrial species into the riparian zone. Since vegetation distribution patterns are strongly correlated with geomorphology (van Coller, Rogers and Heritage, 1997) changes in spatial and temporal patterns of regeneration and mortality in representative reaches form the basis of vegetation TPCs and monitoring the vegetation component of biodiversity.

Table 2. Monitoring the riparian vegetation component of biodiversity of the Sabie River.

Agents of change and rationale: Alluviation will reduce diversity of regeneration niches. Flow reduction will result in a terrestrialisation of riparian zone. Vegetation distribution is strongly correlated with geomorphic diversity. Change in spatial and temporal patterns of regeneration and mortality in representative reaches forms the basis of TPCs.

Measurement Criteria	Measurement Units	Measurement Scale	Thresholds of probable concern (TPC)
Population structure of key species from each of 6 vegetation units:	Size class frequency distribution	Temporal Every 3 years and events greater than 1:25 years	*B. salicina* - negative J-curve population structure in pool/rapid channel types
Breonadia salicina		Spatial All representative reaches except:	Other trees - recruitment at least once in 10 years
Ficus sycamorus		*B. salicina* pool/rapid reaches only	- mortality threshold uncertain *P. mauritianus* - directional increase in areal extent (20 yr prediction)
Phragmites mauritianus *Trichilia emetica* *Combretum erythrophyllum* *Spirostachys africana*		*C. erythrophyllum* alluvial reaches only *S. africana* macro-channels bank only	

Although most understanding of vegetation characteristics is at the community level, the chosen criterion of measurement is the population structure of indicator species of each of 5 of the 6 main vegetation communities (van Coller, et al., 1997) of the Sabie River riparian zone. The sixth community is dominated by *Phragmities mauritianus* Kunth for which the unit of measurement is areal cover. Three of the species, *Ficus sycomorus* L., *Trichelia emetica* Vahl and *P. mauritianus* need to be monitored on all representative reaches. The potential alluviation allows us to reduce monitoring of *Breonadia salicina* Ridsdale to pool/rapid channels types, and *Combretum erythrophyllum* (Burch.) Sond. to alluvial channel types, as these are predicted to be the first channel types to respond to increased sediment storage. The TPCs differ for each indicator species. That for *B. salicina* populations is a loss of a negative J-curve in pool/rapid channel types as this is the primary site of recruitment of this species (de Fontaine, 1995). A directional increase in areal extent of *P. mauritianus* cover over a twenty year prediction period would indicate a change in natural successional sequences (Carter et al, 1995). Little information is available for other tree species but expert opinion suggests that at least one substantial recruitment event every ten years would be enough to sustain populations, provided there was no unusual mortality.

The same process as that described for geomorphology, and outlined in Fig. 4, was used to develop these TPCs and the associated monitoring programme. Models for predicting vegetation response to changing flow and geomorphology are under development. The manner in which continued research is directed by, and services, TPC development (Fig. 4) can be illustrated by this vegetation example. A central assumption underlying the TPCs is that certain channel types will be more susceptible to increased sediment storage and they should thus become the focus of the monitoring programme. A flume based study of sediment transport will use different templates, which will simulate the main characteristics of different channel types, to determine their differential response to a range of sediment and flow characteristics. This will test the hypothesis that pool/rapid channel types will be the first of the bedrock types to become alluviated and support or refute the assumption that monitoring should be focussed on them. Should the hypothesis be refuted the science/management partnership will reassess the indicators used to define TPCs (Fig. 4).

DISCUSSION AND CONCLUSIONS

In contrasting the operational modes of science and management we highlighted the need for science to provide a test of the information collected if it is to be reliable and not degenerate into pseudo-fact. Management, on the other hand, must ensure that broad policy statements are translated into operational, achievable and auditable goals if it is to avoid falling into crisis management and transforming monitoring into a self-serving exercise. Recently a number of ecologists and managers (see references in Costanza , Norton and Haskell, 1992; Gunderson, Holling and Light, 1995; Pickett , Ostfeld, Shachak and Likens, 1997) have emphasised that science/management partnerships need to move away from the traditional species focus towards explicit management of ecosystem heterogeneity, and to the explicit use of societal values to give broader purpose to management.

Some of these concepts are entrenched in the ecosystem health/integrity literature but on the whole river health assessment and monitoring remains largely focussed on a narrow range of taxa (fish or invertebrates) and is seldom explicitly linked to a programme of ecosystem management. Karr and Chu (1997) warn against the proliferation of complex monitoring programmes and emphasise the need to focus on the central components of a clearly defined management agenda. There is however little evidence in the literature that river health or integrity assessment programmes heed this advice. They seem rather to fall foul of many of the problems our contrast of science and management highlighted (Fig 1), and one is left asking what they do with the data they collect?

The clarity and nature of the management agenda must be major determinants of monitoring programme structure and process and thus we can expect that a programme for monitoring ecosystem health could be more parsimonious than one for ecosystem integrity (Karr, 1996) which must encompass the complexity of ecosystem spatial and temporal heterogeneity. Christensen (1997) explains that management of ecosystem heterogeneity must:

1. Explicate objectives in operational terms relevant to ecological function.

2. Develop monitoring programmes which focus on data relevant to those objectives.
3. Provide efficient analysis and management of data.
4. Provide timely feedback from monitoring to managers.

Monitoring linked to such management should focus on management expectations and be designed to test (termed "audit" in this paper) the success and efficacy of management practices. It can also be used to test the hypotheses on which adaptive management is based. Effective management and purposeful monitoring is therefore entirely dependant on the explicitness of links between science, management and auditing processes (Fig. 2).

Costanza (1992) also emphasised that without an adequate operational definition of the desired endpoint, effective management is unlikely. He outlined his concept of an operational definition of sustainable ecosystem health for management as one which;

1. combines measures of ecosystem resilience, balance, organization (diversity) and vigour (metabolism).
2. does not focus on one part of the system as this implies the remaining parts are zero rated.
3. should weight factors to provide a basis for comparing different components of ecosystems.
4. is hierarchical to account for the interdependence of various time and space scales.

Although Costanza (1992) considers his to be an operational definition, at face value it may appear to be rather demanding and more a statement of "desired scientific rigour", than of what managers could realistically implement. It is likely that the resource and expertise requirements of implementing such a comprehensive system would be restrictive in many parts of the world.

The system for integrating indicators, end points and values being implementing in the Kruger National Park provides the clearly defined management agenda advocated by Karr and Chu (1997) in the form of an objectives hierarchy. Furthermore, it adopts the basic principles of ecosystem management outlined by Christensen (1997) and is compatible with many of the principles outlined in Costanza's (1992) definition.

The Kruger rivers science/management partnership meets Christensens' criteria in the emphasis placed on developing a monitoring programme that is focussed on clear operational goals. It also provides and structured feedback between partners to test both the success of management and the value of scientific input. Furthermore, the concept of system spatial and temporal heterogeneity is firmly entrenched in the selection, description and measurement of a wide range of indicators, end points (TPCs) and values.

There is great potential for the monitoring of heterogeneity to become complex (Karr and Chu, 1997), inefficient (Christensen, 1997) and costly. In the Kruger National Park this is overcome by the parsimonious selection of criteria, appropriate temporal scales of measurement and the spatial restriction of monitoring to representative reaches. Such parsimony would not easily have been obtained without the explicit science/management partnership which has been developed.

Costanza (1992) sees health as a measure of the overall performance of a complex system that is built up from the behaviour of its parts. Indicators provide direct measures of a component's status, endpoints are composites of these indicators, and health is defined with the help of societal values. Our use of these terms differs slightly from those of Costanza but this reflects the practicalities of operationalizing a management programme under specific constraints and needs, rather than differences in interpretation of the principles they embody.

Our system embraces indicators of a number of ecosystem components and is based on a hierarchical understanding of system structure and function (Pickett and Rogers, 1997). As yet we do not formally weight different ecosystem components as Costanza's definition requires but our focus on indicators of agents of change and first order responses to change, implicitly weights them higher than other measures. For example measures of change in community composition are more distant from the cause of change and can lead to more reactive, after-the-fact, management responses. Since TPCs represent acceptable levels of change in the systems we manage they are also indicators of ecosystem resilience. It remains to be seen how well they perform! Future monitoring and modelling exercises (Fig. 3) will determine this as part of the cycle of adaptive management.

One of the biggest challenges faced in ecosystem management is to break out of our scientific cocoons and purposely integrate scientific principles and knowledge with seemingly vague and potentially conflicting societal values (McDonnell and Pickett, 1993). Kruger Park management has attempted to integrate values and scientifically defined endpoints into an objectives hierarchy.

A hierarchical integration of societal and scientific goals (Fig. 3) has a number of advantages. First, it overcomes the potential for conflict, or divergence of messages, sent to the manager because it ensures compatibility of the goals of these different sectors. Second, a hierarchically organised definition of the desired condition of the rivers can serve the needs of different levels of the management hierarchy with statements which demonstrate the same intent but use terminology appropriate to the users needs.

Since we recognise the importance of hierarchical scaling in dealing with ecological issues it makes sense to also derive a hierarchically differentiated definition. Indeed, it is probably a bit naive to always attempt a single universally acceptable definition or goal statement. When dealing with the public or press, the CEO of a conservation agency needs a very different description of management goals from that which provides direction for the field manager. A hierarchically arranged definition provides the basis for generating a compatible set of definitions which all reflect the same set of desired conditions but have potential for use for a range of purposes.

Thus, most of the theoretical underpinnings of management for sustained ecosystem health/integrity can be operationalized if clear and achievable goals are available to guide the process at different levels of a science/management organisational structure.

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Appendix 2

Challenges for catchment management agencies

Lessons from bureaucracies, business and resource management

K Rogers[†], D Roux* and H Biggs[‡]

[†] Kruger National Park Rivers Research Programme, Centre for Water in the Environment, University of the Witwatersrand, Private Bag 3, WITS 2050, South Africa

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Abstract

Catchment management agencies (CMAs) have no tested precedent in South Africa and will have to evolve in complex and changing business, social and natural environments as they strive to ensure that equity and social justice are achieved within ecological limits. Traditionally, very different styles of management have been used for resource exploitation and resource protection and this will present a serious dilemma for CMAs.

As the human population has grown and natural resources have declined, there has been increased effort to control nature in order to harvest its products and reduce its threats. Initially such "command and control" management has been successful as agencies prosper on short-term gains. However, when natural variation is reduced the ecosystem loses its resilience and ability to "bounce back" from disturbances. The first lesson we can learn is that the longer term consequence of command-and-control management is always either a reduction or cessation of

resource supply.

The second lesson comes from adaptive resource management (ARM).ARM acknowledges that, because nature is in a continual state of flux and our understanding of ecosystem functioning is poor, a fundamental problem for decision makers is that they must deal with uncertainty from an imperfect knowledge base. A learning-by-doing approach becomes a prerequisite for effective management. Unfortunately, there has been a tendency to superimpose adaptive management on bureaucratic institutional structures. Such flouting of the fundamental management axiom "form must follow function", has thwarted many attempts at adaptive management. This provides our third lesson.

Recognition that authoritarian, command and control, bureaucracies respond too slowly to survive in changing environments has led managers in government, industry and businesses to create "learning institutions" which combine adaptive operations and generative leadership (lesson four). Effective knowledge management is seen as a critical success factor in turning command-and-control management into adaptive, learn-by-doing management (lesson five).

CMAs which recognize the dangers of excessive command and control, the need to integrate stakeholder values and activities, and the potential of an adaptive and generative management approach, will need to structure their activities carefully.

At present there is much focus on the structure of CMAs and much less on how they should function. Form is preceding function in many instances. When function is discussed it centers on how regulatory mechanisms and permit systems will keep resource use under control. The concern is seldom with how the ecosystem will be managed. This sort of thinking could lead to a classic command-and-control management approach if not tempered with a more adaptive process.

Strategic adaptive management (SAM) is a local derivative of ARM designed to generate consensus management which is inclusive, strategic, adaptive and creative. SAM is a process in which effective knowledge management is central to building a partnership between science, management and society to achieve a common vision. It has considerable potential for application to CMAs.

Introduction

South Africa's new Water Law is commendable for its mix of "water use for development" and "protection of the resource" but are we aware of the dilemma this creates for the catchment management agencies (CMAs) which must protect the ecosystems which supply the resource they use.

The dilemma comes from the different styles of management which have been traditionally used for resource exploitation and those that are needed for resource protection. In most countries these two functions are performed by different agencies. It is a dilemma compounded by paradigm shifts which democratization of decision making and the global explosion of knowledge, force on managers and government in South Africa. For example:

- CMAs have no tested precedent and will have to evolve in complex and changing business, social and natural environments. They will have to be adaptive, learning organizations. This will be no mean feat for an organization born out of a government bureaucracy.
- CMAs will find that by far the majority of decisions in a catchment are made by individual land owners/resource users. They will need to ensure inclusive, participatory management which exposes and meets the needs and values of stakeholders.
- CMAs will find themselves relying on consultants to perform many functions and this will fragment and dissipate any knowledge base they attempt to build. Effective knowledge management will be paramount to successful service delivery and resource protection.
- CMAs will have to ensure that equity and social justice are achieved within ecological limits if they are to meet the full requirements of the new Water Law. Sustainable

development and sustained ecosystem functioning will need to have explicit and audited outcomes.

These problems are however not as unique as one might expect and are receiving attention in disparate fields of natural resource management, business and governance. We should take time to learn from others during this period of renewal in South Africa.

When learning from others we need to make a particular effort to understand the paradigms or mental models (Senge, 1990) which lie behind their approach to the problem. In each case a discipline has its own terminology which provides important definition of its guiding principles. In this paper we recognise that one persons "jargon" may be another's definitive criteria and have tried to remain faithful to the range of disciplines from which we draw inspiration. Where discipline specific terms differ from common English usage they are either explained or referenced.

There are three complementary sources of concern and inspiration for the topic under discussion:

- Recognition of the consequences of command-and-control management as practiced by bureaucracies.
- The discipline of adaptive resource management (ARM).
- Moves in industry, business and even government to build "learning institutions" which will promote the transition from the information era to the knowledge era.

Command-and-control management

Control is a deeply entrenched aspect of contemporary human societies. As the human population grows and natural resources decline, efforts are increased to control nature in order to harvest its products and reduce its threats, and thus to produce predictable outcomes (Holling and Meffe, 1996).

When the behaviour of people, institutions or nature violates the norms, desires or expectations of society, command and control is brought to bear in an effort to move the institutions, and/or the ecosystems, to a stable and therefore predictable state. We dampen extremes of ecosystem behaviour to attain a predictable flow of goods and services, or to reduce "undesirable" behaviour of natural processes. A universal result of command-and-control management of natural resources is a reduction of the natural range of variation in ecosystem properties and processes (stable flow regimes in rivers, canalization of rivers, stable animal numbers at so-called carrying capacity by culling or harvest quotas, suppression of fire, monocultures of crops etc.). When the range of natural variation in a system is reduced the system loses resilience and its ability to "bounce back" from the human and natural disturbances it will inevitably experience. The longer term consequence has always been a reduction, or even cessation, of resource supply (Holling and Meffe, 1996).

The initial phase of command-and-control resource management is nearly always successful as agencies prosper on short term gains. Consequently the agencies shift their attention from the system under management to increasing efficiency of operation and delivery to society. Though a laudable goal in itself, this generally results in a myopic introspective focus which shifts from research and monitoring of the resource response, to exploitation, to internal agency function and power plays. Then, when the inevitable vagaries of nature, or economics, intervene the agency takes too long to respond from an out-of-date, superficial knowledge base. A decline in quantity or quality of the resource is inevitable.

Institutional bureaucracies themselves are an exercise in variance reduction through regulation and control. A certain amount of administrative procedure is always needed but its purpose must be to improve service delivery not control social behaviour. Too often bureaucracies adopt as their main purpose regulation and control to eliminate extreme behaviour and promote conformity to a specific set of standards. We saw some extremes of this during the apartheid era.

Entrenched bureaucracies are characteristically resistant to change and unable to respond to challenges because the system discourages innovation or other behavioural variance. The difficulties experienced in transforming parastatal institutions, regional and national government in South Africa are good examples.

It is imperative that we consider carefully the type of institution and operating style we wish to develop for CMAs if we want to avoid this pathology of natural resource management and ensure the protection of the ecosystems which provide the water resource.

Adaptive resource management (ARM)

Although the concept of ecosystem management is generally accepted there is only one widely recognized model for management of natural resources, and that is ARM (Walters, 1986, Holling, 1978). ARM is an approach to management which acknowledges that because nature is in a continual state of flux and our understanding of ecosystem functioning is poor, dealing with uncertainty from an imperfect knowledge base is central to effective management. The original intent of adaptive management was therefore that it be an inductive process utilizing well planned interventions in nature to test hypotheses of ecosystem response to management and thus learn-by-doing (Walters and Holling 1990).

Adaptive management has a sound theoretical base but planning adaptive management systems has proven easier than implementing them on a long term basis. The main problem and a dominant theme in current international literature is how the process can be institutionalized (Walters, 1997; Rogers, 1998) without invoking a command-and-control response? In instances where there has been no appropriate, explicit and sustained institutionalization, adaptive management systems have tended to be unsustainable. Our synthesis and interpretation suggest that contributory issues are:

5. Decision making becomes overwhelmed by too much information which in unsifted form can paralyse the decision-making process.
6. Implementation becomes bogged down by the tyranny of modelling and modellers in pursuit of the ultimate model/technology. Walters (1997) has termed this "the battle of the models".
7. Monitoring programs designed to support an adaptive approach to management have generally been too ambitious (Walters, 1997) and unachievable within the organization's resource constraints.
8. There is too much turf protection by "managers" and "scientists" who both pay lip service to co-operation and are not sufficiently committed to effective science/management partnerships (Rogers, 1998) which can only work as groups of equals.
9. Individuals and organizations are unable to adapt to the new ways of thinking, functioning and structuring which institutionalizing an adaptive philosophy and approach

demands. There is a tendency to superimpose the adaptive management process on old, usually bureaucratic, institutional structures and processes. In other instances the old familiar operating rules soon "roll back" when the new system leaves staff feeling out of their comfort zone. Both ignore the fundamental management axiom of "form must follow function" when planning or changing institutions.

Recent conferences and workshops on CMAs that many regional Deapartment of Water Affairs and Forestry offices are falling foul of this axiom. There is a rush to set up structures to form the precursors of CMAs, without due regard for the processes needed to perform their intended function. These structures are being designed under old, or only partially modified paradigms which have not fully explored the sorts of issues raised in this paper.

Once again we must modify the structure and functioning of our organizations to ensure that they can deal adaptively with the resource use/protection dilemma, and other problems the CMAs will face, in a learning-by-doing manner.

Creating adaptable "learning institutions"

An equally recurrent theme in business management is the understanding that sustainable business requires the capacity for on-going learning and continuous transformation (Allee, 1997). Over the last decade managers in industry and businesses have become aware of the need to "create learning institutions through a combination of adaptive and generative leadership" (Senge, 1990). Senge describes an adaptive process as one of "coping" and a generative process as one of "creating". Such a distinction has not been made in resource management but perhaps it should be, especially in the context of creating learning institutions for adaptive management.

The need for learning institutions in business and industry has been empirically demonstrated. Most Fortune 500 companies have a life half as long as a person's work life but the few which have survived for 75 years (a short time in the context of water resource management) or longer, did so because they ran "experiments" to explore new business AND organizational opportunities continually (Senge, 1990). Such companies also changed from "top down control" (where the person at one organizational level instructs the person at a "lower" level what to do) to "integrative thinking and acting on all levels". This change is due to recognition that authoritarian bureaucracies respond too slowly to survive in the changing environment which is a fact of life for all operations today.

There is now much emphasis in business on making "on-going learning" an explicit part of management, and on making knowledge management (as opposed to mere data or information management) an explicit and successful part of learning. Knowledge has come onto centre stage for successful business and is seen as "information, combined with experience, context, interpretation and critical reflection". Reynolds (1998) emphasizes the need for reflection to be critical. This is the antithesis of what happens in a typical bureaucracy. Davenport et al. (1998) surveyed 31 knowledge management projects in 21 companies and identified success factors for creating, transferring and using knowledge more effectively:

1. Knowledge-friendly culture,
2. Clear purpose and language,
3. Senior management support,
4. Multiple channels of knowledge transfer,
5. Change in motivational practices to reward learning as opposed to doing,
6. Appropriate technical and organizational infrastructure,
7. Link to service performance,
8. Flexible knowledge structure.

This learning and knowledge orientated paradigm shift is not restricted to private enterprise. In the United States, a National Performance Review is evaluating how to "reinvent government" by assessing how government organizations can be made more hospitable to learning and creativity in improving service delivery. Barth and Bartenstein (1998) suggest that the emphasis on reflection and theory testing found in academics can be combined effectively with the action orientation of practitioners to generate creative, learning organizations even within government bureaucracies. They emphasize the value of such an adaptive organizational structure and process for maintaining effective service delivery in response to changing societal demands.

An explicitly learning institution is therefore seen as the viable alternative in business, natural resource management and government to the command-and-control bureaucracies, the limitations of which are now broadly accepted. Improving knowledge management is the common theme in moves to create learning organizations which in turn are seen as essential for success in a rapidly changing environment. Effective knowledge management could be a key success factor in turning command-and-control management into adaptive, learn-by-doing management, and we ignore it at our peril.

Strategic adaptive management (SAM)

The concept and practice of (SAM) (Rogers and Bestbier, 1997; Rogers, 1998; Rogers and Biggs, 1999) is a local derivative of ARM designed to generate consensus management which is inclusive, strategic, adaptive and creative. SAM is a process which is both dependent on and instrumental in, building a partnership between science, management and society. It is explicit about developing context and encouraging reflective (adaptive) interpretation. Like ARM it is dependent on explicit management of the knowledge at its disposal, and needs a formal model to guide institutionalization.

Central to SAM is a consultative process whereby stakeholders (science, management and society) utilize scenario planning to integrate their visions (Rogers, Roux and Biggs, 2000) into a consensus view of the Desired State of the system to be managed (Fig. 1). The desired state takes the form of an objectives hierarchy which translates a consensus vision of future societal needs and values, into operational goals (Rogers and Bestbier, 1997). These goals provide managers on the ground with both institutional (administrative) targets, and specific ecological endpoints for ecosystem management (Rogers and Biggs, 1999).

The process of incorporating values into the desired state and defining it in achievable terms, is one way of condensing knowledge into manageable units. A second is enshrined in the process of selecting a small group of indicators which is used to measure achievement of goals. Monitoring is focused on these indicators and is expressly designed to be practical within resource constraints.

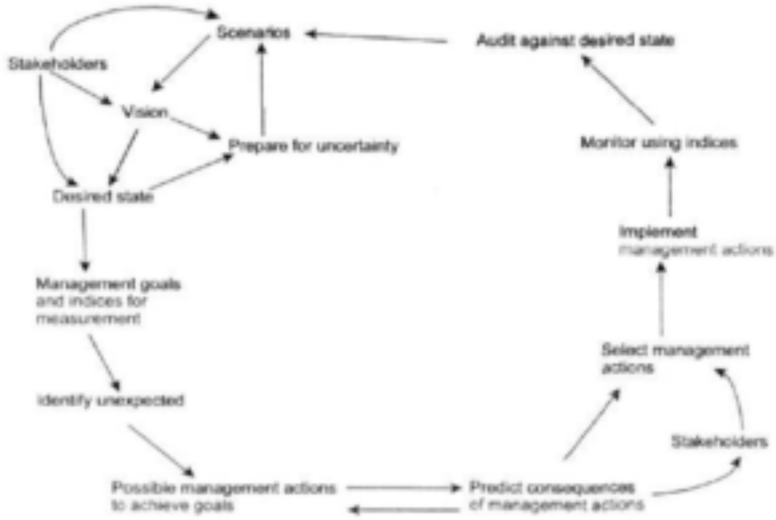

Figure 1. The fundamental components of a Strategic Adaptive Management System

Further scenario generation is coupled with predictive modelling to outline a range of possible management actions and their likely consequences (Fig. 1). Relevant stakeholders within the science/management/society partnership are thus equipped to select the most appropriate management options for implementation. Such explicit evaluation of alternatives avoids the all too common response of reactive selection of the most immediately available solution (Rogers and Biggs, 1999).

Following implementation, monitoring of the chosen indicators is expressly aimed at auditing goal achievement against the desired state (Fig 1). Future scenario projections can be used to complete an iterative loop, adapting and learning at each iteration.. The process must be iterative and must treat all scenarios and goals as hypotheses, or best estimates, to be challenged and tested as the knowledge base grows.

Institutionalizing strategic adaptive management

CMAs which recognize: a) the dangers of excessive command and control, b) the need to integrate stakeholder values and activities and c) the potential of an adaptive and generative management approach, will need to structure their activities carefully. The above discussion suggests five factors critical for successful institutionalization of a process such as SAM (Fig. 2):

1. **Integrated operations**. It is essential to reduce territoriality amongst stakeholders and to blur the lines between who are managers, who are scientists/researchers and who are the deliverers and receivers of goods and services. All are contributors to service delivery and resource protection in the context of an inclusive, learning institution adopting SAM. Within an institution it is important to redefine "Operations" involving both scientists and logistics personnel who undertake actions supporting increased system assessment, evaluation and understanding through collection of data and knowledge. They differ only in the emphasis on physical action by logistics personnel who manipulate the ecosystem and the emphasis on hypothesis testing by scientists who audit goal achievement (Rogers and Biggs, 1999). Defining the role of other stakeholders and integrating their activities into overall catchment management activities is a largely unexplored arena in South Africa.

2. **Strategic knowledge management**. This node is responsible for generating wisdom which leaders use for decision making. Control of the quantity, quality and form of information reaching the Leadership (Fig. 2) node is imperative for effective decision making. Knowledge management is about strategically and creatively reducing the complexity of data and information into knowledge and wisdom in order to facilitate effective decision making (Mayers, 1996). As such it moves an organization well beyond the confines of mere information management. The work of a knowledge manager has three foci: 1) generation of knowledge which entails its creation, acquisition, synthesis and adaptation; 2) codification of knowledge centers on its capture, transformation and representation; 3) transfer of knowledge between locations and, most importantly, ensuring its absorption by the recipient (Meyers, 1996). Reducing knowledge of ecosystem structure/function and stakeholder needs into an objectives hierarchy and a few achievable goals is an important aspect of knowledge reduction in SAM. Integrating the stakeholder knowledge base, including the fast disappearing indigenous traditional and cultural knowledge will be a central challenge of this node?.

Figure 2. A framework for institutionalizing Strategic Adaptive Management

3. **Decision making**. Joint forum decision making ("acting on all levels"; Senge, 1990) is essential in institutions adopting SAM. This does not and should not remove responsibility from the agency, or its Executive Management, for decision making but rather facilitates it. Such decision making can entrench intra-institutional integration and reduce the chances of Operations becoming a self-serving bureaucracy. The desire for action by staff on the ground must be balanced by reflection about the problem and potential solutions (c.f. Rogers and Biggs, 1999).

4. **Common Knowledge, Purpose and Process**. Ensuring that all stakeholders operate from a common knowledge base and with united purpose (e.g. for an agreed desired state) will markedly reduce conflict and increase co-operative governance within a catchment. Its central importance must not be underestimated and considerable effort will need to be expended in activities to serve this node. Common purpose is achieved by collaborative goal setting and auditing. It provides the cement and building blocks of integrative, shared and creative management. Processes/protocols for setting visions/goals and running an organization adaptively must be explicit, documented and adhered to. Command and control will inevitably appear as the agency grapples with the dual needs for participatory, adaptive management and the common process needed to streamline operations. The challenge will be to keep it within the bounds of administrative procedure and prevent it

from limiting participation by society in decision making processes.

5. **Nurturing institutional environment.** None of the above will be achieved without the unambiguous creation of a culture which stimulates institutional learning and embodies the philosophy behind SAM. The culture provides the inspiration for integrative, shared and creative adaptive management. The essence of such a culture would be to promote;

   i) sharing of responsibility amongst stakeholders rather than apportioning blame,

   i) a shared-territory/stewardship across boundaries spirit,

   ii) learning-by doing,

   iii) inspired and critical reflection/hypothesis testing,

   iv) dealing with uncertainty, complexity and change as given factors,

   v) balance demands for altruism with personal incentives,

   vi) in a South African context, Ubuntu (I see you the individual), Simunye (we are one) and Batho pele (people first).

Developing this culture requires a move away from regulatory, authoritarian line management, towards a new style of generative leadership (Senge, 1990). Generative leaders are defined as;

- **designers** of common purpose and core values, of strategies and structures for guiding decisions, and of effective learning processes.
- **teachers** who help people achieve more accurate, insightful and empowering views of reality.
- **stewards** for both the people and the vision of the enterprise.

This kind of leadership is imperative if CMAs are to serve the common purpose of resource delivery and protection in our emerging democracy.

Discussion

The authors have collectively participated in many formal and informal discussions on this subject. We acknowledge that our knowledge is incomplete, but are nevertheless concerned that there is insufficient awareness of the potential for command and control management of water allocation to dominate CMA activities. Resource protection is in danger of playing second fiddle.

To highlight this concern we contrast two perspectives of how the Water Act may be implemented. The first perspective (Fig. 3) was gained from discussions on the Water Protection Policy implementation which DWAF personnel are tackling so professionally and courageously (DWAF, 1999). We emphasize that this is our interpretation and recognize that the issue is under debate even within DWAF. We hope the contrast we make here will promote discussion and aid in achieving more clarity.

Figure 3. An interpretation of the management cycle for implementing the new South African Water Act

The initial impression is that of an iterative, and therefore potentially adaptive, process (Fig. 3). However, the way this iterative loop is portrayed (Fig 4) and the way some managers seem to be interpreting it (e.g. the absence of an ecosystem manager in proposed CMA structures), also conveys the impression that the resource, in particular the ecological reserve, would not itself be managed. It would only be protected by default through application of an administrative system which limited the number of permits/licences for water use.. This would amount to a classic case of command-and-control management.

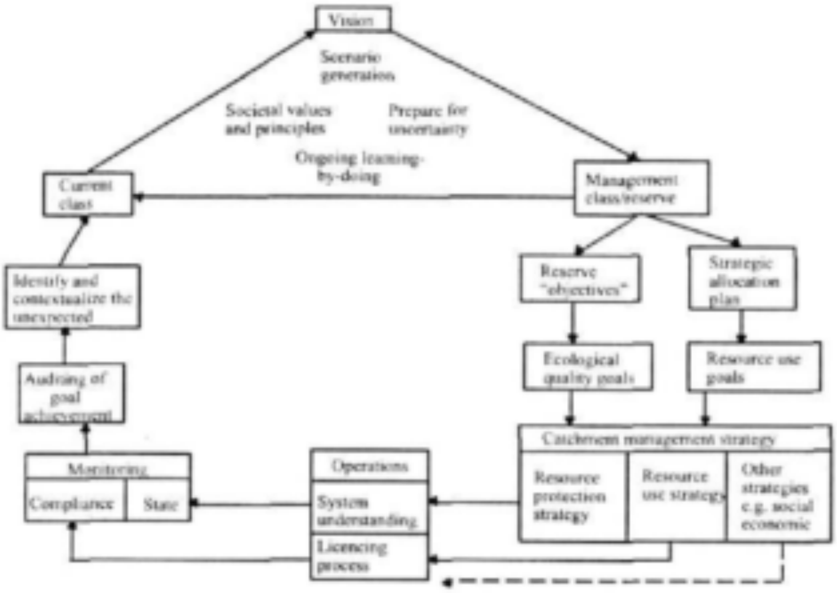

Figure 4. A strategic adaptive perspective for implementation of the new Water Act

This is clearly not the intention of the National Water Policy which requires that a "balance" be achieved between (1) the setting of Resource Quality Objectives to be achieved by the ecological reserve and (2) a system for managing and controlling water use through authorisations and licences. In other words the aquatic ecosystem must also be explicitly managed to achieve the desired resource quantity and quality as described by the Resource Quality Objectives. Simply limiting the amount of water use by command-and-control licencing does not constitute achieve ecosystem management and explicit provision must be made in CMA strategies and structures for appropriately trained ecosystem managers.

This illustrates why it is so difficult to combine resource use and resource protection in one organization, particularly when that organization (e.g. a CMA) is built from the expertise of another (e.g. DWAF) which has no history of managing ecosystems. It will take considerable adaptation of mind set to over come these problems. A contrast of the leadership style, structure and culture of conventional bureaucracies with adaptive organisations should provide water managers with examples of such adaptations in mind set (Table 1).

To assist discussion around this subject we merged our SAM process (Fig. 1) with the perspective we gained from DWAF (Fig. 3) to develop a prototype model for a strategically adaptive process for managing both the water use (licencing) and resource protection components described in the Act (Fig. 4). Perhaps the model is naive but it may provide a basis for discussion. The key features are:

- An iterative process of relating current state of the system with desired state in the context of unexpected changes to the system.
- A hierarchical process for decomposing the management class into achievable goals.
- Parallel but interactive strategies for the range of social, water use and protection catchment management activities
- Similarly parallel processes for monitoring goal achievement and responding to changes in state.

This model emphasizes general processes. It will be extremely challenging to convert these into operational processes but that is beyond the scope of this paper which aims only to highlight issues which need serious debate as we attempt to implement new policy.

At present, much discussion centers on the structure of CMAs and much less on how they should function to facilitate the implementation of these processes. Form is preceding function in many instances. When function is discussed it often centers on regulatory mechanisms and permit systems. These are essential elements but have the potential to invoke a classic command-and-control *modus operandi* if not tempered with a more adaptive process. We hope that the contrast above provides a basis for holistic planning to avoid such an approach and to stimulate parallel and actively managed mechanisms for balancing resource use and protection.

Table 1. A contrast of leadership style, organisational structure and organisational culture in conventional bureaucracies and adaptive organisations.

Issue	Conventional bureaucracies	Adaptive organisations
Leadership style	Primarily command-and-control Transactional/paper shuffling	Primarily to coordinate and facilitate Generative (designer, teacher, steward)
Structure	Functional hierarchies Vertical communication Work *for* one boss	Dynamic teams with blurred boundaries Horizontal dialogue Work *with* colleagues across boundaries
Culture	Thinking at the top doing at the bottom Collect data and mange information Follow rules and regulations Internal competition This-is-our-product/empire syndrome Observe and criticise mistakes Rather make no decision than a wrong one View uncertainty, complexity and change as threats	Develop common purpose through collaborative goal setting Generate, codify and transfer knowledge Driven by vision and values Integrated operations across stakeholder-service provider boundaries Enthusiastic sharing of knowledge (Trust and openness) Learn and adapt through hypothesis testing and critical reflection Recognise when new knowledge allows you to make the next better decision Treat uncertainty, complexity and change as opportunities for learning and improvement

South Africa is in a unique phase of renewal in which there is unprecedented opportunity to implement lessons already learnt elsewhere in the world. These lessons are not easily implemented in countries where entrenched bureaucracies hinder progress (c.f. Gunderson, et al., 1995). We should not waste this opportunity to catch up with, and even pass, other global economies and democracies. The use of our Water Law as a text book example by international universities (Mackay, pers. com.) indicates that it has achieved this status. We must be sure that the institutions we set up to implement and administer this law are equally innovative and do it full justice. If not, the progressive legislation will flounder in the face of bureaucracy.

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Modelling geomorphic change along the Sabie River, Kruger National Park: Updating SEDFLO model predictions for the period 1932-2000.

1 Introduction, background and objectives

The sediment flux and storage model (SEDFLO) described by Birkhead and James (2000) and Birkhead *et al.* (2000) predicts the temporal and spatial distribution of sediment accumulation along the Sabie River within the Kruger National Park (KNP). The river is represented by 40 linked cells, each characterised by one of the five principal channel types identified by Heritage *et al.* (1997a), including, alluvial single thread; alluvial braided; mixed anastomosing; bedrock anastomosing and pool rapid. SEDFLO consists of two integral components. The first component deals with the production of sediment across the catchment landscape and the delivery of this eroded source material to the study length of the river in the Kruger National Park. This includes lateral inputs from tributaries. The second component of the model deals with the differential transport of the sediment along the 110.5 km study river system.

The first phase is performed jointly using the Calibrated Simulation of Transported Erosion model (CALSITE) and Agricultural Catchments Research Unit model (ACRU). The CALSITE results for the Sabie River subcatchments are accepted as being the most accurate (Donald, 1997), and the output is in terms of annual sediment yield. SEDFLO operates on a daily basis, however, and these annual values are therefore distributed temporally according to the daily variations predicted by ACRU.

In SEDFLO, the sediment transport through each channel type cell is calculated by the widely accepted total load equation of Ackers and White. The model was calibrated for the Sabie River using historical information describing changes in sedimentation obtained from aerial photographs, as reflected by changes in coverage by alluvial bars.

Application of SEDFLO (Birkhead and James, 2000) indicated a long-term (1940-1986) change in sediment storage for the Sabie River within the KNP of approximately 3.5 thousand tons/annum. Shorter-term changes in sediment storage were highly variable, reflecting periods of progressive sediment accumulation, interspersed by significant declines during years experiencing large flow events. The average increase in sediment storage during periods of progressive accumulation was as high as 40 thousand tons/annum, while the loss of sediment during years experiencing large floods was generally greater than 200 thousand tons.

The predicted changes in sediment storage have been shown to be realistic when compared with sensible changes in alluviation along the length of the Sabie River, as well as with the rate of siltation of the dam at Lower Sabie. The modelling of pre 1940 change within the bedrock anastomosing channel types showed significant losses of sediment storage. Although there is no historical data to test this finding, a sequence of observed change from aerial photography suggested the occurrence of a series of large floods in the late 1930s that stripped alluvial deposits from a bedrock anastomosing section of the river.

The model was applied to flow sequences representing modifications to the original historical sequence in accordance with the ecological flow recommendations developed for the major rivers in the catchment. The flow sequences were simplified in that they did not include dam spillage or drought period requirements, but they did account for the reduction of sediment inflow associated with reduced river flows. The following conclusions were drawn from the scenario modelling:

- Long-term rates of alluviation increase approximately proportionately with reduced mean annual runoff (MAR).
- Transient sediment storage behaviour is reduced by diminished flooding. This is likely to impact significantly on the spatial and temporal assemblages of geomorphological features and associated aquatic and riparian habitats, since under conditions of reduced flooding, sedimentation reduces the proportional occurrence of bedrock influence in the system.
- In adjusting to new dynamic equilibrium states in response to a reduced flooding regime, alluvial channel types tend to erode whilst pools and (to a lesser degree) mixed anastomosing channel types tend to aggrade. Loss of storage in braided channel types is likely to result in a smaller active channels, incised within the macro-channel infill deposit.

The objectives of this work are to:

- update the SEDFLO model predictions of temporal and spatial distribution of sediment accumulation along the Sabie River up to and including the year 2000, and
- assess the model predictions for the extreme flood event experienced in February 2000.

2 Extended flow and sediment yield data

The ACRU model provides simulated discharge and sediment yield at a daily time step for 56 subcatchments comprising the Sabie River system. The SEDFLO modelling described by Birkhead *et al.* (2000) used ACRU simulations for the period 1932 to 1993. The update described here uses the latest ACRU simulations, extending to the end of the year 2000. The ACRU model updates were undertaken by A. Pike (School of Bioresources Engineering and Environmental Hydrology, University of Natal).

Figure 1 is a plot of the annual runoff simulated by ACRU for the period 1932 to 2000, showing both the 1993 and 2000 simulations (i.e. for the periods 1932-1993 and 1932-2000, respectively). The plots show that the updated (2000) parameterisation for the Sabie River catchment predicts generally lower annual discharge volumes. The MAR for the 40 river cells are plotted in Fig. 2. The updated estimate of the MAR for the 62 year period (1932-1993) has reduced by 18% from 823 million m^3 to 676 million m^3. The MAR for the 68 year period (1932-2000) is higher at 744 million m^3, with 1867 million m^3 and 3753 million m^3 having been discharged in the flood years 1996 and 2000, respectively. Since Figs 1 and 2 are plots of runoff volumes on an annual basis, it cannot be established where these changes occur in the updated flow regime, i.e. in the low flows, high flows, or both. The SEDFLO model was calibrated based on the 1993 ACRU simulations, and it is necessary to identify where these changes are reflected in the modelled historical flow regime (Fig. 1).

Figure 3 is a plot of the 1-day flow duration curves for the Sabie River at its entry to (cell 1) and exit from (cell 40) the KNP, using the 1993 and 2000 ACRU simulations. The flow-duration curves show that the ACRU update (2000) produces consistently lower daily flows over a range of discharges (0.6-100 m^3/s) for equivalent exceedance values. The marked drop in discharge at high exceedance values (95% (2000) and 97% (1993) for cell 40) reflects the occurrence of simulated no flow conditions. The infrequent nature of floods (and limited duration) result in a low exceedance values, which are difficult to interpret from Fig. 3. Figure 4 therefore provides a plot of the annual peak flows (mean daily) for the period 1932-1993. The updated (2000) parameterisation of ACRU predicts lower flood peaks compared with the 1993 simulations, by up to 1000 m^3/s for the highest (2500 m^3/s) and 30 m^3/s for the lowest peak annual flows (84 m^3/s), respectively. High flows have been shown to account for a large proportion of the sediment transported in river systems with extreme flow regimes (Heritage *et al.*, 1997b), and changes in the high flow component of the modelled flow regime will influence the SEDFLO calibration and application described by Birkhead *et al.* (2000). The sensitivity of SEDFLO predictions to the updated ACRU hydrology needs to be assessed.

As mentioned previously, the annual sediment yields from the CALSITE model are distributed temporally according to the daily variations predicted by ACRU. Changes in the daily simulated sediment yields are of less relative consequence than the (water) discharges, which are used directly as input to SEDFLO. Figure 5 is a plot of the sediment inputs to the SEDFLO model estimated from a combination of (i) either the 1993 or 2000 simulated daily sediment yields from ACRU; (ii) the long-term sediment delivery estimate of CALSITE; and (iii) the calibration of sediment inputs described by Birkhead *et al.* (2000). The average sediment discharge from the Sabie River into cell 1 (western boundary of the KNP) has reduced by 29%, whereas the Sand River input into cell 34 has increased by 13%. The smaller tributary inputs have changed by 1%, and are less important in relation to the overall input (the sediment discharges to cells 1 and 34 constitute 68% of the overall sediment delivery to the study length of the Sabie River).

Changes in the modelled hydrology (and to a lesser extent sediment yield) for the Sabie River catchment, which is required as input to the SEDFLO model, will influence its calibration (which is based on a previously simulated data set for the period 1932-1993) and predictions. Although this is not ideal, it provides an opportunity to assess the sensitivity of the SEDFLO model results to input data.

The fact that flows in rivers are only manageable to a certain extent, particularly in semi-arid environments such as the Lowveld region of South Africa, which is characterised by large variability in rainfall and runoff (Heritage *et al.*, 1997a and Pienaar, 1985). This was reaffirmed during the recent devastating floods experienced in this area during February 2000 which resulted in loss of life, left many people homeless, and caused immense damage to infrastructure. Initial indications are that the floods have resulted in extensive changes in the fluvial geomorphology and distribution of riparian vegetation along the Sabie River, with associated changes in habitat availability to riverine biota. These severe, though natural, floods provide excellent opportunity to study the recovery of riverine ecosystems within the Sabie River following extreme flow events. This is made possible by previous studies of the geomorphology (Heritage *et al.*, 1997a and Birkhead *et al.*, 2000). These changes in the river morphology will also influence the predictive accuracy of SEDFLO, through altered river cross-sections and hydraulic characteristics.

Recalibration of the SEDFLO model to account for changes in the hydrological, topographical and hydraulic behaviour will require substantial resources and a protracted effort, beyond the scope of this study. It is also unrealistic to expect that model re-calibration to take place whenever significant changes to the input data occur, considering the level of predictive accuracy achievable from the model (refer to Birkhead *et al.*, 2000). For these reasons, the model parameterisation described by Birkhead *et al.* (2000) is adopted for this update, and the nature of the predictions are assessed accordingly.

3 SEDFLO model predictions: 1932-2000

The net change in sediment storage in the channel type cells along the Sabie River (KNP) for the period 1993-1996 are plotted in Fig. 6. The graph shows very little correspondence between application of the 1993 and 2000 ACRU input data sets, with only 4 of the 40 cells indicating the same directional change, i.e. net reduction or accumulation of sediment. This demonstrates the sensitivity of net modelled changes in storage resulting from the updated hydrology and sediment inputs (as presented in Figs 1 to 5).

The temporal changes in sediment storage for the river (all cells) are plotted in Fig. 7 for the periods 1932-1993 and 1932-2000, and show marked differences in the predicted net change in storage (-704 vs. 703 thousand tons at the end of 1993). Using the 2000 input data, SEDFLO predicts a higher long-term rate of increase in storage (approximately 11.5 compared with 3.5 thousand tons/annum (1940-1986)), and the loss of storage associated with the years experiencing large floods is also reduced. These results are expected, given the changes in modelled hydrology discussed in Section 2, which reveals reduced discharge rates across the entire flow regime (refer to Figs 3 and 4).

Also plotted in Fig. 7 are the predicted changes in temporal storage allowing no sediment loss or accumulation in the bedrock anastomosing channel type cells (fine lines in Fig. 7). This allows the relative contribution of these channel types to sensible storage change to be assessed, given that their erodible storage capacity is limited by underlying bedrock. The differences are more marked for the 1993 simulations, which have a higher modelled flooding regime (Fig. 4). The differences are particularly noticeable for late 1930's and the year 2000 using the 1993 and 2000 modelled hydrological data, respectively. Birkhead *et al.* (2000) provided a sequence of observed change for a bedrock anastomosing channel type (cell 12), for the years 1940, 1986 and 1996. The 1940 exposure shows a river devoid of any sediment and riparian vegetation, and suggests the recent occurrence (prior to the 1940 exposure) of an extreme flood or series of events. Based on these records, it was not possible to determine the pre-1940 sediment storage status of the bedrock anastomosing channel types and consequently the potential for large scale erosion. The propensity for bedrock anastomosing channel types to scour during extreme flood events (Birkhead *et al.*, 2000) is supported by using the updated hydrology for the flood experienced in 2000 (modelled peak mean daily flow of 2600 m^3/s at the Mozambique border). Large scale stripping of consolidated alluvial deposits from bedrock anastomosing channel types resulted from the 2000 floods, corroborating the predictions of SEDFLO. If unlimited (simulated) removal of material is permitted from these channel types, it accounts for approximately 6 times the net sediment removed from the river system (Fig. 7), although realistically, the removal of sediment would be limited by the underlying bedrock.

Notwithstanding the changes in modelled hydrology presented in Section 2, the storage behaviour predicted by SEDFLO is consistent. The short-term changes are variable, reflecting periods of progressive accumulation, interspersed by significant reductions during years experiencing large flow events. The model predicts a net reduction in sediment storage in the Sabie River resulting from the extreme flood event experienced in 2000 by between 314 and 976 thousand tons (limiting and allowing unlimited removal of material from the bedrock anastomosing channel types, respectively). This has resulted in a storage state comparable to that last experienced by the river prior to 1950. High flows and floods act to reduce the net sediment storage in the river that accumulates during drier periods containing relatively fewer high flows.

Figure 7 presents a plot of the net change in sediment storage for the length of river in the KNP, and it is useful to assess how these changes are distributed in the principal channel types. The highest reduction in storage (annual) using each of the two ACRU simulations (1993 and 2000) are plotted in Fig. 8. These are for the year 1939 which had a peak mean daily flow and annual runoff volume of 1156 m^3/s and 2904 million m^3 (3.5 times the MAR) respectively (1993 simulation), and the year 2000 which had a peak daily flow and volumetric runoff of 2600 m^3/s and 3753 million m^3 (5 times the MAR) respectively (2000 simulation). The purpose of using both hydrological data sets is to illustrate that the directional change for 39 of the 40 cells are the same, even for the different years in which large floods were experienced.

Although a net loss of sediment from the river system is associated with large floods (Fig. 7), the directional change for the different channel types and individual cells are complex. Figure 8 indicates that large floods remove sediment stored in bedrock anastomosing channel types (all 9 cells indicate loss); braided channel types tend to accumulate material (all 11 cells indicate aggradation), whilst single thread, pool-rapid, and mixed anastomosing channel types both increase and reduce their storage. The reason for these changes in storage, associated with high magnitude flows, become apparent when assessing the potential sediment transport rate characteristic of the principal channel types (refer to Heritage *et al*., 1997b). Bedrock anastomosing and braided channel types exhibit the highest and lowest potential transport capacities at high flows, respectively, with the other three channel types falling in-between. The change in storage for any cell is a function of the sediment transported from the upstream cell including catchment contributions (i.e. tributary inputs), and the ability of the cell itself to transport sediment. For all cases therefore, braided channel types tend to accumulate sediment during floods, and bedrock anastomosing channel types tend to erode unless they have large tributary inputs.

For the other three principal channel types, the change in storage for a cell is very much dependant on the relative transport characteristics of the upstream cell, i.e. the relative difference in transport characteristics. For example, any channel type downstream of a bedrock anastomosing channel type will tend to accumulate sediment, and any channel type downstream of braided channel type will tend to erode. Tributary inputs may, however, alter the water-sediment discharge balance downstream of their confluence with the main stem. As a further example of this, a pool rapid channel type downstream of a mixed anastomosing channel type will tend to erode during large floods, since it exhibits a higher potential to transport sediment at high flows, as indicated by the change in storage for cell 33 in Fig. 8. This highlights the necessity of treating river systems as a continuum when predicting morphological change, because the storage state of a site along a river depends on its transport characteristics relative to the upstream river section.

Following subsidence of the February 2000 flood waters, there was much anticipation to assess whether the event had resulted in large-scale stripping or accumulation of sediment along the Sabie River. Somewhat disappointedly, considering the extreme nature of the event, the only consensus that has emerged so far is that the change in sediment storage has been complex and variable. Certain sections of the river appear to have accumulated sediment whilst others have had material removed. The results from SEDFLO for the 2000 floods support this apparently indecisive opinion of the effect of the floods. Although the results indicate a net loss of some 976 thousand tons (Fig. 7), the distribution of this net loss, as illustrated in Fig.8, indicates both loss and accumulation of the same order on a cell or channel type scale. For particular channel types the change is directional (i.e. bedrock anastomosing and braided), whereas for others (single thread, pool-rapid and mixed anastomosing) it is variable and depends on their relative positioning along the river system.

Figure 7 shows that during periods of below average runoff (refer to Fig. 1), net alluviation of the river occurs (e.g. for the period 1962 to 1970). The river system displays a pattern of dynamic storage behaviour, and the loss associated with large flood events (as depicted in Fig. 8) can be expected to be reversed during "dry" periods of below average runoff where relatively fewer high flow events are experienced. This is necessary to maintain the dynamic equilibrium illustrated in Fig. 7, avoiding the unattainable condition (over the long-term) where certain channel types accumulate sediment indefinitely, and vica-versa.

Figure 9 is a plot of the change in storage for the 8 year period from 1962 to 1970, in which the highest mean daily flow was 261 m^3/s and the MAR was only half the 68 year value of 744 million m^3. The modelled changes in sediment storage for this dry period confirm the requirement stated above for dynamic equilibrium. As before, the directional change in storage during periods experiencing limited flooding is directly related to the ability of the different channel types to transport material, with the braided and bedrock anastomosing channel types having the highest and lowest capacities at low flows, respectively (refer to Heritage *et al.*, 1997b).

Figure 10 is a plot of the relative changes in storage for the period 1932 to 2000 for the five representative channel type cells (refer to Birkhead *et al.*, 2000). The plots illustrate complex temporal storage behaviour on a cell basis. The flow related behaviour of the braided and bedrock anastomosing cells can be expected to be relatively generic (i.e. related to channel type), whilst that for cells of the remaining three channel types (single thread, pool rapid and mixed anastomosing) depends on their position within the river continuum (not only their channel type).

4 Implications for management of physical processes in the Sabie River system

These findings have implications for the management of physical processes in the Sabie River system. The results indicate that there exists a complex balance between the flow (and sediment) regime of a river; the sediment transport characteristics of the channel types along the system; their relative position within the continuum, and their resulting storage state. Upstream water resource developments effectively alter the natural flow-duration regime for the downstream river, altering the complex balance of these determinants of storage. For example, bedrock anastomosing channel types appear to accumulate sediment during minor flood events and intermediate flows (Figs 9 and 10), and reducing the occurrence of such events will effectively retard the recovery process that would have resulted naturally after extreme (but natural) flood events have stripped sediment from these sections of the river.

Therefore, to maintain the natural geomorphological character of the river (including its temporal change), it is necessary to ensure that the natural variability in the flow regime is maintained (i.e. the shape of the natural flow duration curve is not materially altered). In river systems that display a highly variable flow pattern, such as the Sabie, this is not achievable, since infrequent flood events cannot be managed or controlled. It is therefore crucial that the magnitude and occurrence of smaller floods and lower flows (that are influenced by upstream developments) are maintained within a modified flow regime. Failure to do so will likely result in a change to the dynamic balance of sediment inputs; transport capacity; and resulting sediment storage - with implications for the natural recovery that would be expected to occur after an extreme flood as experienced in 2000.

It is difficult to determine the degree to which the construction of the Injaka Dam on the Marite River (tributary of the Sabie River) will alter the rivers flow regime without considering this as a development scenario in ACRU. Previous attempts to quantify this (Birkhead *et al.*, 2000) allowed only for the ecological flow recommendation, and did not provide for spillage from the dam. Attempts to improve on this have not been successful, since the temporal flow demands on the Injaka Dam have not been established. In addition, operating procedures to supply the ecological flow requirements for the Marite River (particularly high flows when the dam is not spilling), need to take account of natural flows in the catchment - to maintain natural variability and ensure that high flow releases coincide with those in the Sabie River. A more realistic development scenario will best be achieved by incorporating the Injaka Dam (and future demands on it) in the configuration of the ACRU model for the Sabie River catchment.

5 Conclusions

SEDFLO is a relatively robust model for predicting directional change in sediment storage along the Sabie River. The predicted storage behaviour for the period 1932-2000 is consistent using two different modelled input hydrological data sets. The short-term changes are variable, reflecting progressive accumulation during dry periods containing relatively few high flows, interspersed with reductions in net storage during years experiencing large floods.

The directional change for the different channel types and individual cells (of given channel type) in response to large floods, is complex. High flows tend to remove sediment stored in bedrock anastomosing channel types, whilst braided channel types tend to accumulate material. Cells of channel types single thread, pool rapid and mixed anastomosing display variable changes in storage, depending on their relative position along the river system. This highlights the need to treat river systems as a continuum when predicting morphological change, since the storage state of a site depends on its transport characteristics relative to the upstream river section. The Sabie River displays a pattern of dynamic storage behaviour, and the loss associated with large flood events is reversed during drier periods of below average runoff where relatively fewer high flows are experienced. This results in dynamic equilibrium within the system, which is largely a function of flow variability. The dynamic balance of flow and sediment inputs from the catchment; ability of the river to transport material; and resulting sediment storage; need to be maintained within a managed flow regime. This will ensure that the natural recovery, that would be expected to occur following extreme floods, takes place. The predictions support the general opinion that the change in sediment storage along the river, resulting from the 2000 floods, has been both variable and complex.

Note:
The reasons for the differences in predicted ACRU hydrology were referred to the modeller responsible as soon as they became apparent in this study. It has only recently come to light that a "major problem with the new (2000 ACRU simulation) configuration files which would probably explain all the differences between the 1993 and 2000 simulations due to irrigation extractions taken from incorrect sources" (A. Pike, pers com). The findings presented in this document should therefore be reviewed when the corrected ACRU simulations are available and SEDFLO has been rerun. It is unlikely that this will significantly effect the results of the updated SEDFLO predictions. This is because the differences in modelled hydrology have not materially changed the SEDFLO predictions - when analysed in terms of directional change for the river system as whole as well as at the channel type scale. Furthermore, irrigation extractions should not influence modelled high flows, which have also been shown to be reduced in the 2000 simulations used in this study (refer to Fig. 4).

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Figure captions

Figure 1 Simulated annual runoff volumes from ACRU for the Sabie River catchment for the periods 1932-1993 and 1932-2000, using the 1993 parameterisation and 2000 update.

Figure 2 Mean annual runoff volumes along the Sabie River in the KNP using the 1993 ACRU model parameterisation and 2000 update.

Figure 3 1-day flow duration curves for the Sabie River at its entry to (cell 1) and exit from (cell 40) the KNP, using the 1993 and 2000 ACRU simulations.

Figure 4 Exceedance curves for the annual peak flows (mean daily discharges) from the 1993 and 2000 ACRU simulations, for the period 1932-1993.

Figure 5 Mean annual sediment input to the Sabie River (KNP) from the 1993 and 2000 ACRU simulations.

Figure 6 Net modelled change in sediment storage for channel type cells along the Sabie River (KNP) for the period 1993-1993 applying the 1993 and 2000 ACRU simulations (BA = bedrock anastomosing; BR = braided; MA = mixed anastomosing; PR = pool-rapid; ST = single thread).

Figure 7 Modelled change in sediment storage for the Sabie River (KNP) from the 1993 (1932-1993) and 2000 (1932-2000) ACRU simulations (The fine lines indicate the condition whereby no sediment loss or accumulation is allowed in the bedrock anastomosing channel type cells).

Figure 8 Modelled change in sediment storage for the years 2000 (2000 ACRU simulation) and 1939 (1993 ACRU simulation) for the channel type cells along the Sabie River (BA = bedrock anastomosing; BR = braided; MA = mixed anastomosing; PR = pool-rapid; ST = single thread).

Figure 9 Modelled change in sediment storage for the dry period 1962-1970 for the channel type cells along the Sabie River (BA = bedrock anastomosing; BR = braided; MA = mixed anastomosing; PR = pool-rapid; ST = single thread).

Figure 10 Modelled change in sediment storage from 1932 to 2000 for the five representative channel type cells along the Sabie River.

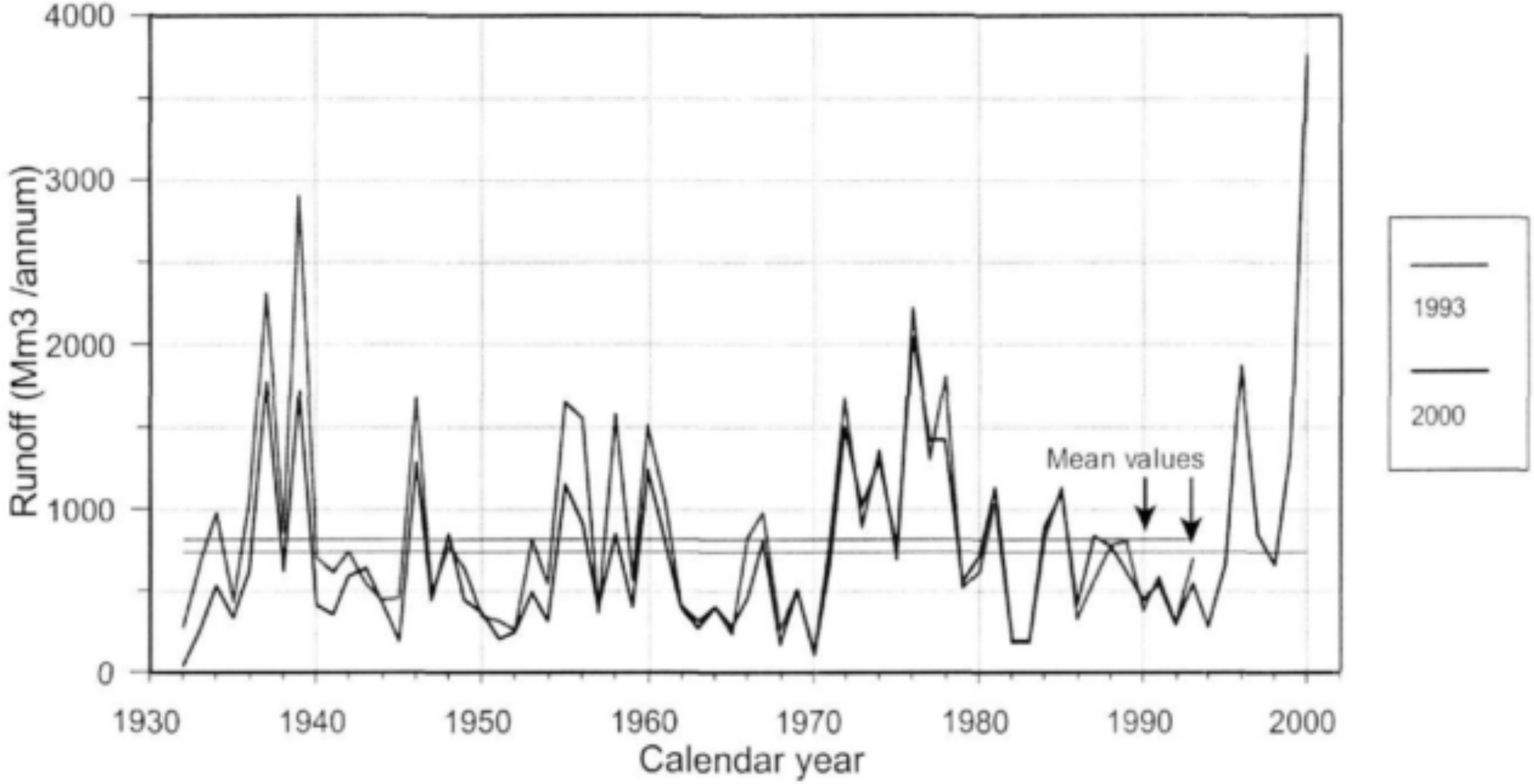

4000
3000
2000
1000
0
Runoff (Mm3 /annum)
1930
1940
1950
1960
1970
1980
1990
2000
Calendar year
Mean values
1993
2000

Fig. 1

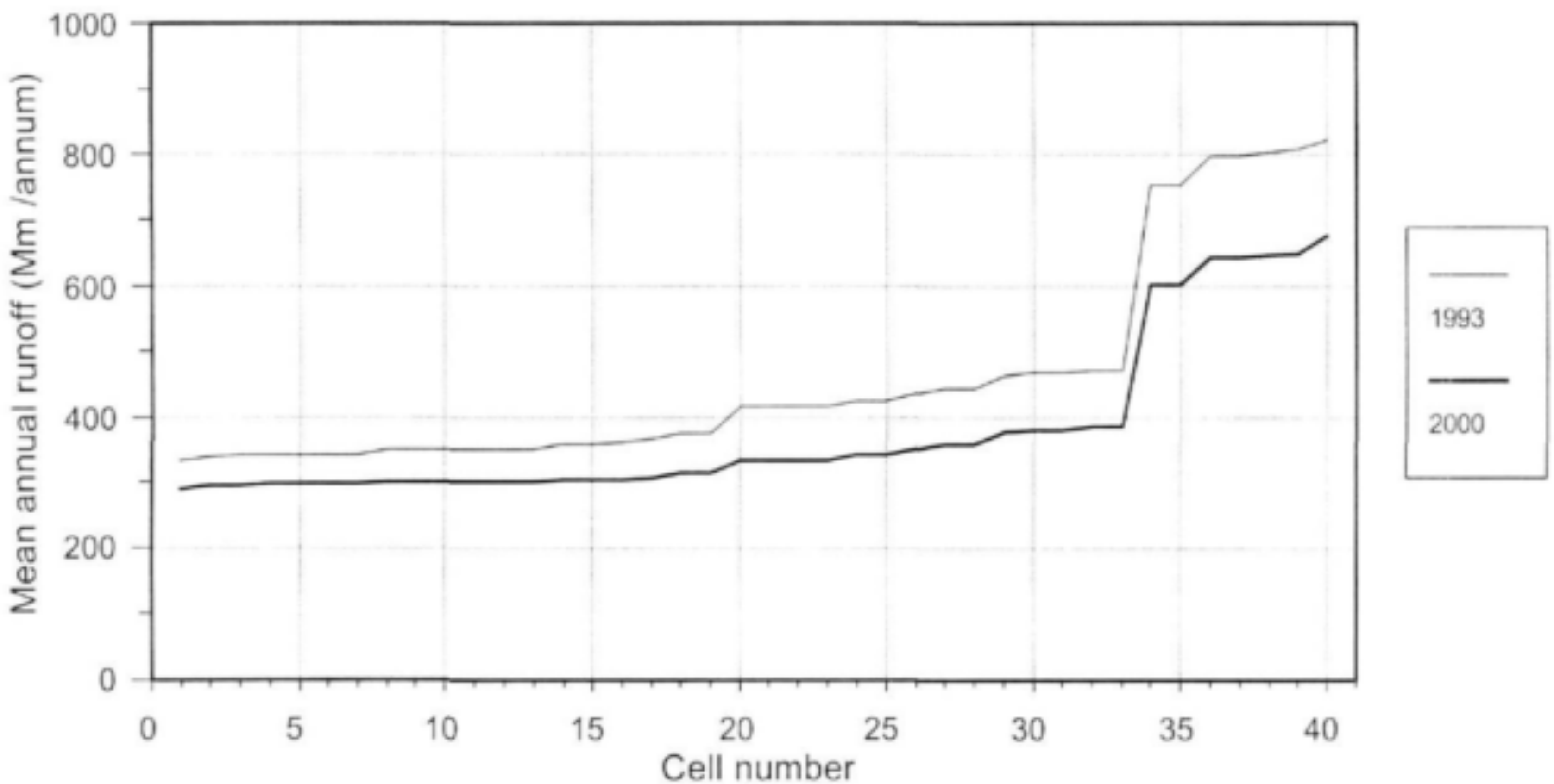
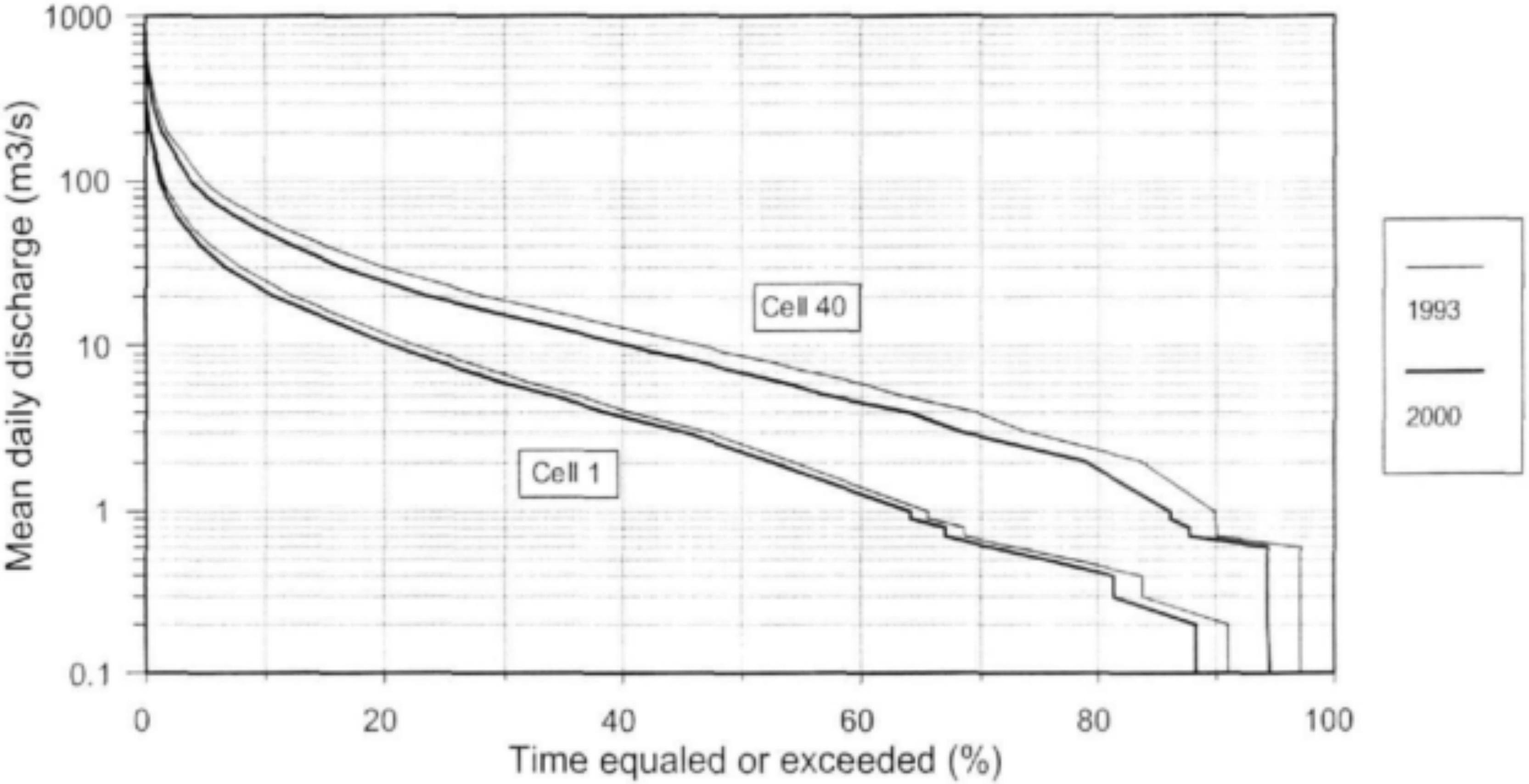

Mean annual runoff (Mm /annum)
1000
800
600
400
200
0
0
5
10
15
20
25
30
35
40
Cell number
1993
2000

Fig. 2



Mean daily discharge (m3/s)
1000
100
10
1
0.1
0
20
40
60
80
100
Time equaled or exceeded (%)
Cell 40
Cell 1
1993
2000

Fig. 3

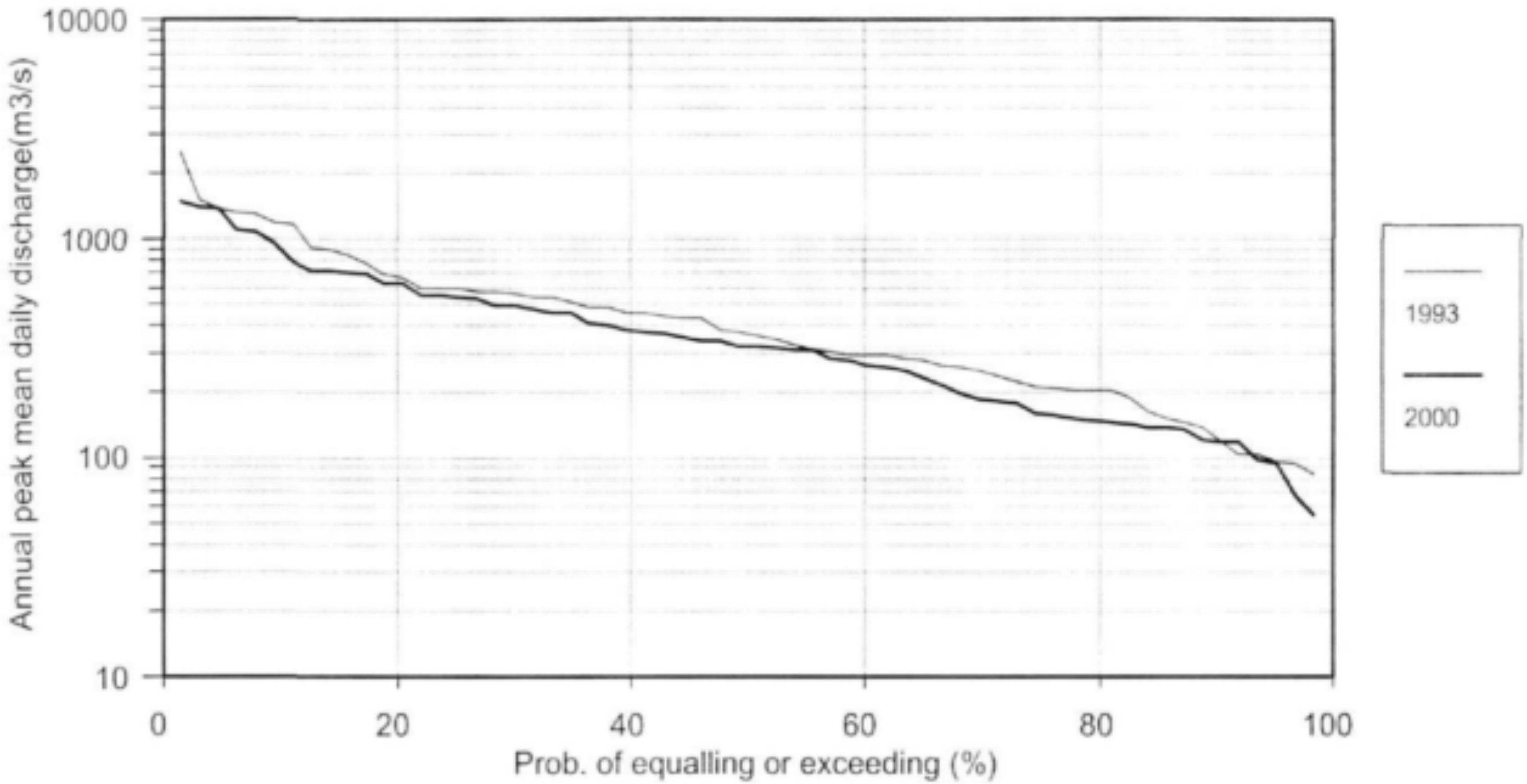

10000
1000
100
10
Annual peak mean daily discharge(m3/s)
0
20
40
60
80
100
Prob. of equalling or exceeding (%)
1993
2000

Fig. 4

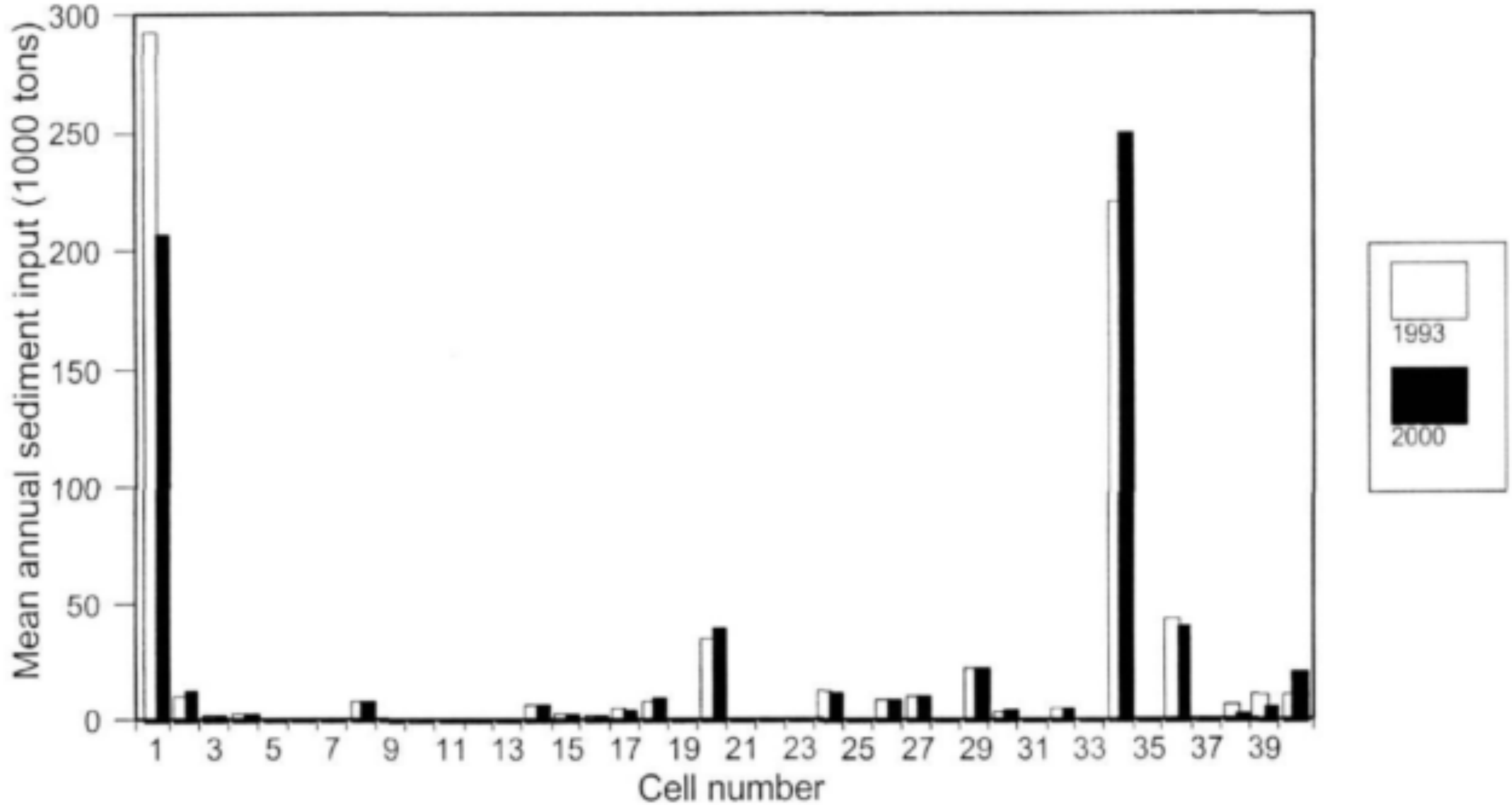

Mean annual sediment input (1000 tons)
300
250
200
150
100
50
0
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
Cell number
1993
2000

Fig. 5

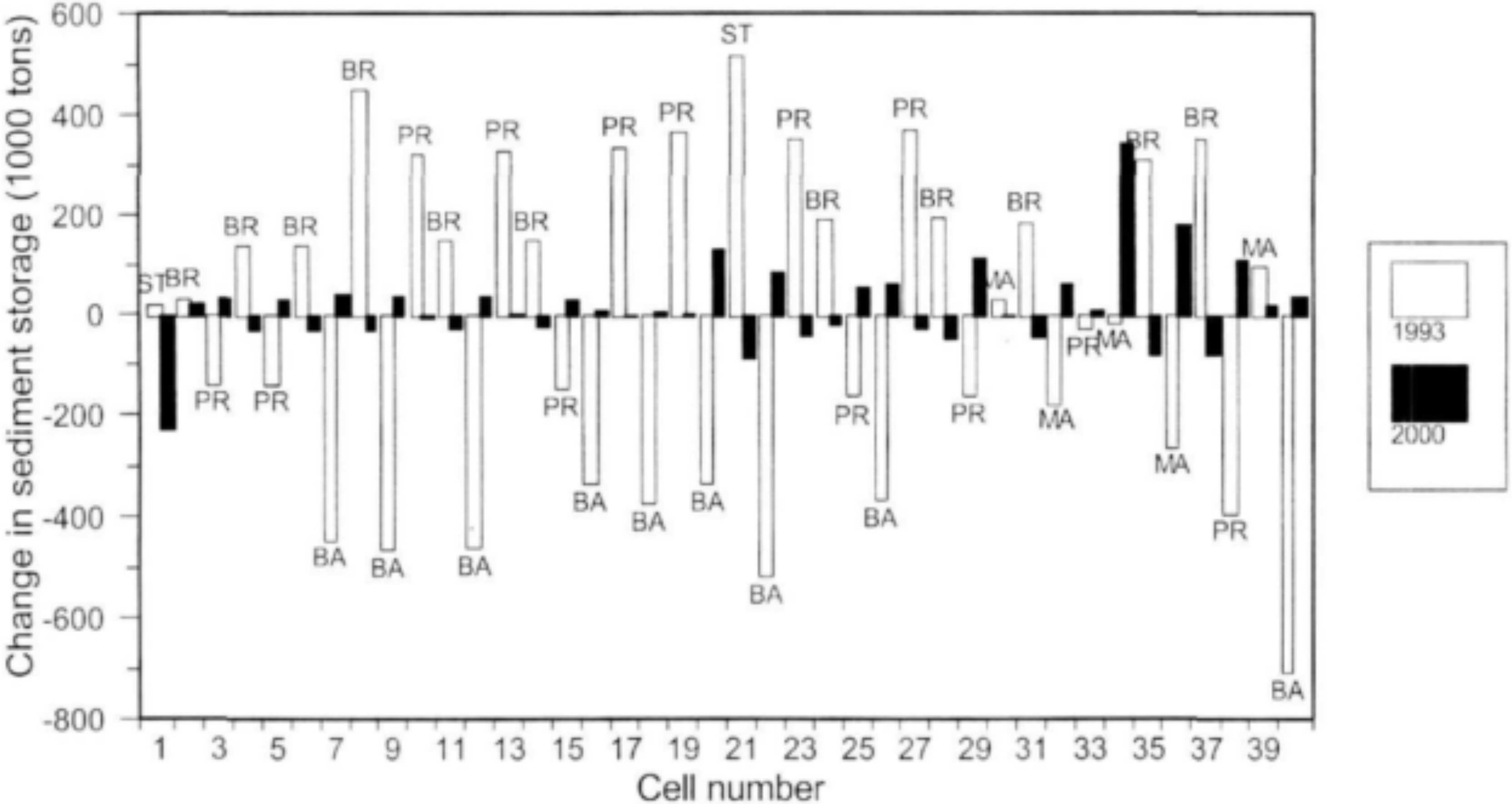
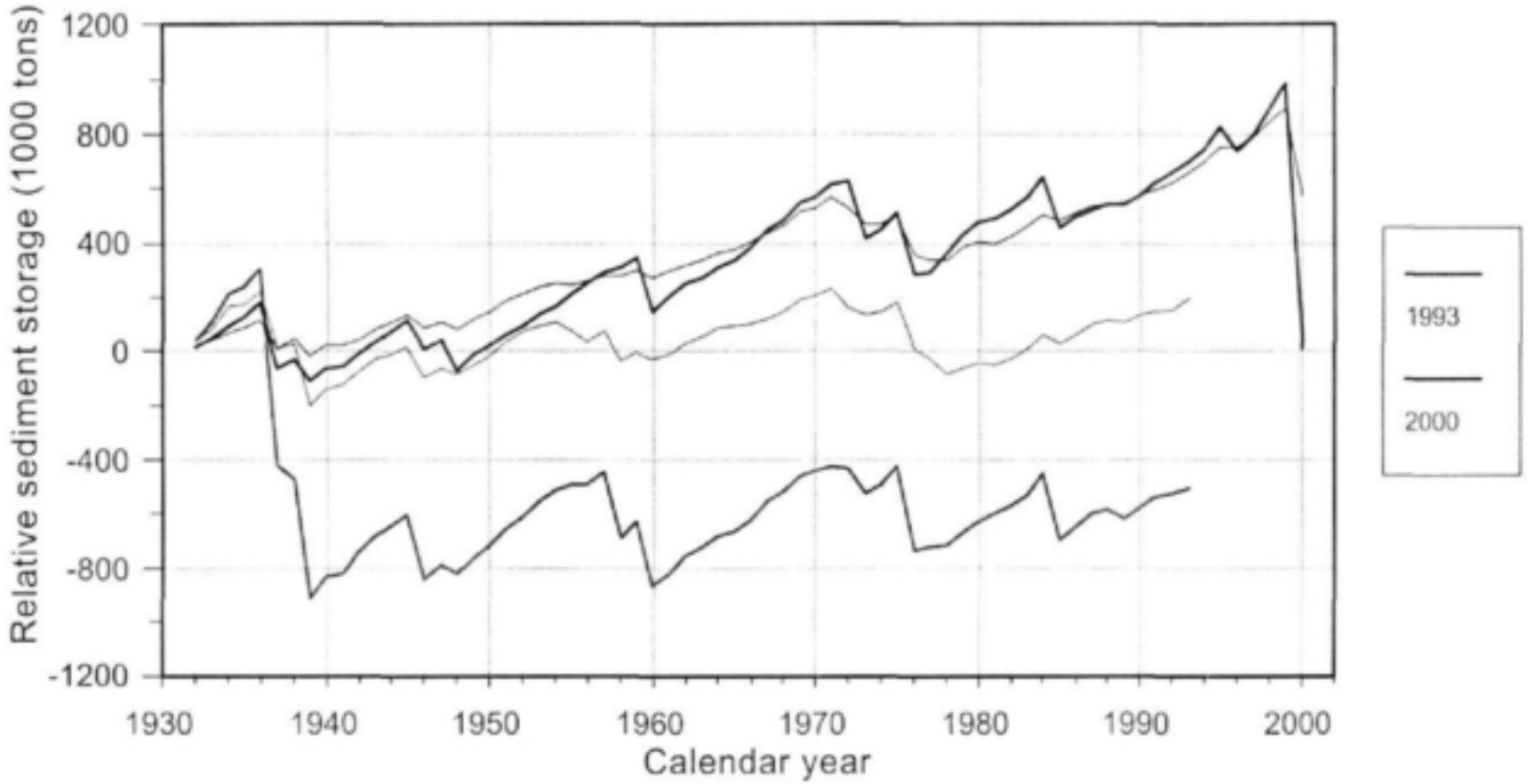

Change in sediment storage (1000 tons)
600
400
200
0
-200
-400
-600
-800
Cell number
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
ST BR BR BR BR PR BR PR BR PR PR ST PR BR PR BR BR BR BR MA
PR PR BA BA BA PR BA BA BA BA PR BA PR MA PR MA MA PR BA
1993
2000

Fig. 6



Relative sediment storage (1000 tons)
1200
800
400
0
-400
-800
-1200
1930
1940
1950
1960
1970
1980
1990
2000
Calendar year
1993
2000

Fig. 7

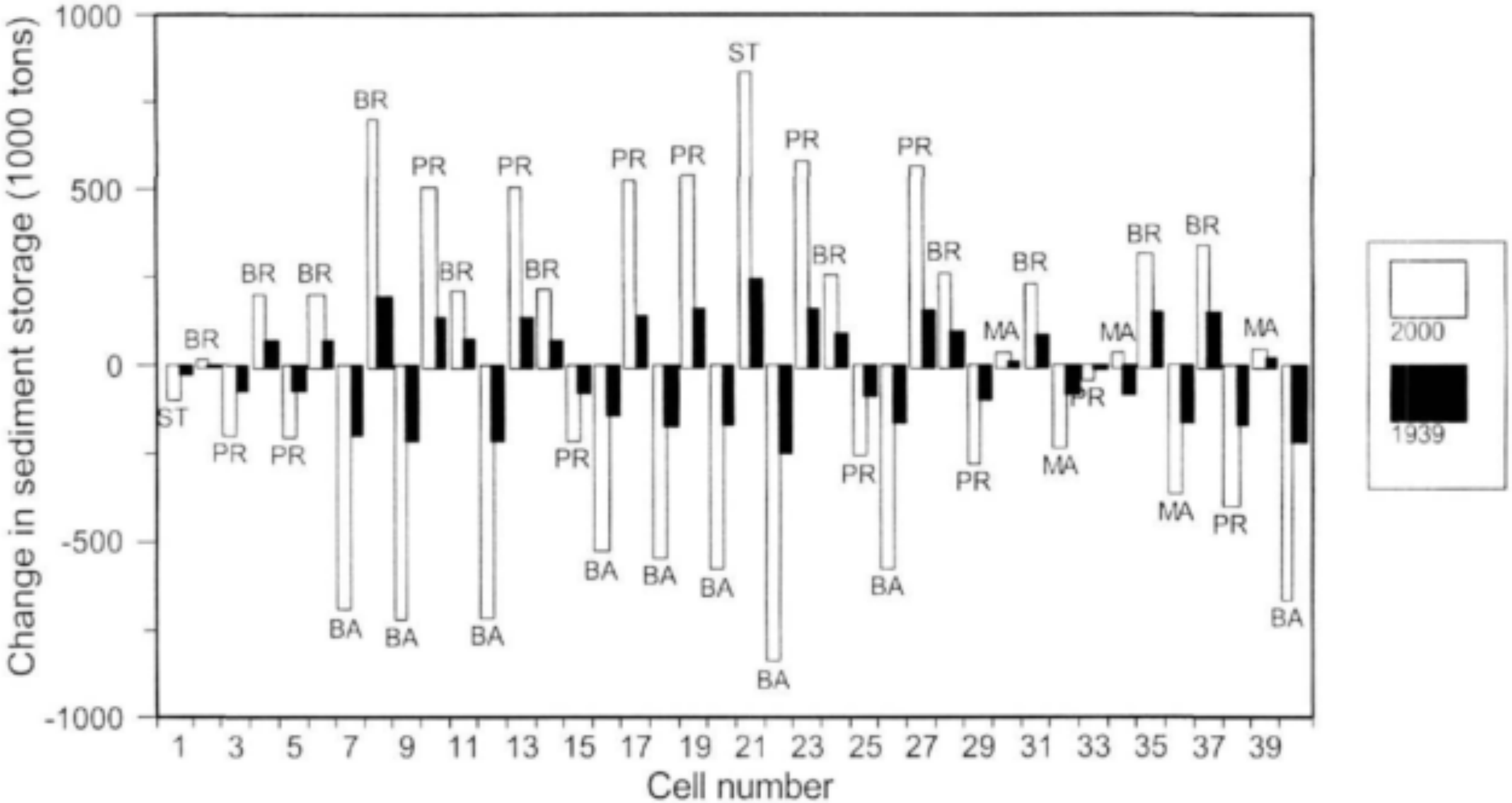


Fig. 8

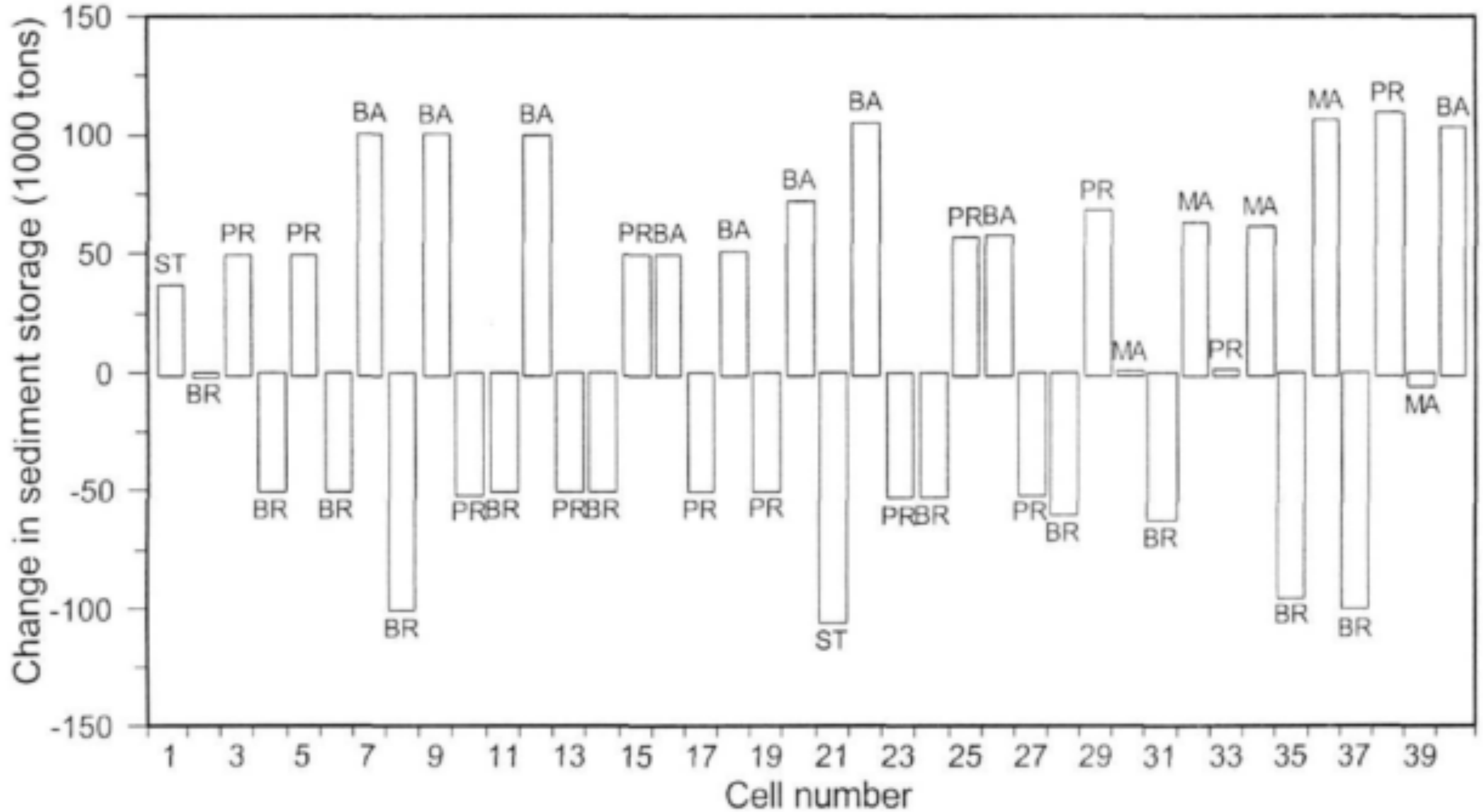

Change in sediment storage (1000 tons)
Cell number
150
100
50
0
-50
-100
-150
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31 33 35 37 39
ST BR PR BR PR BR BA BR BA PR BR BA PR BR PR BA PR BA PR BA ST BA PR BR PR BA PR BR PR MA BR MA PR MA BR MA BR PR MA BA

Fig. 9

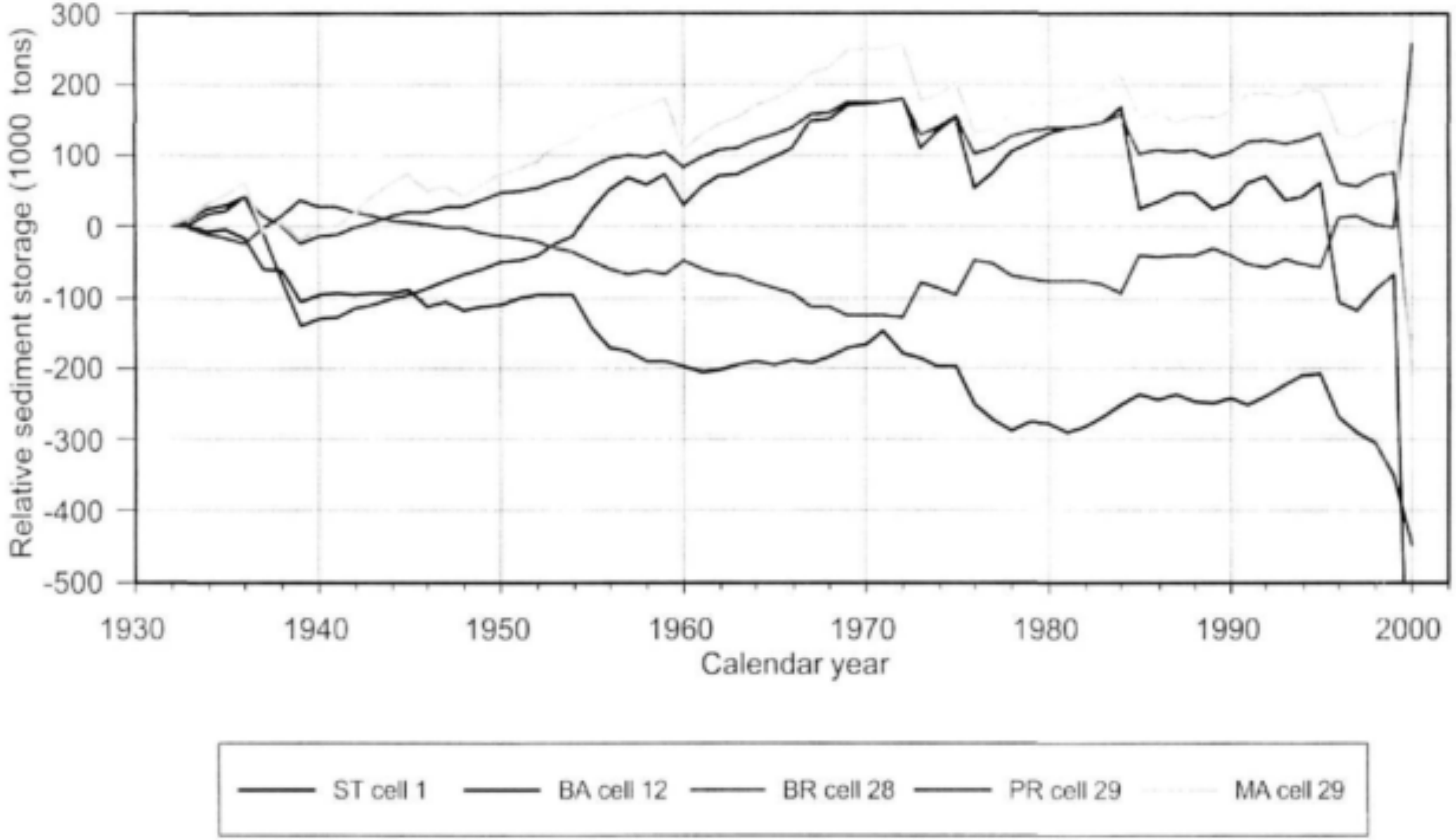

300
200
100
0
-100
-200
-300
-400
-500
Relative sediment storage (1000 tons)
1930
1940
1950
1960
1970
1980
1990
2000
Calendar year
ST cell 1
BA cell 12
BR cell 28
PR cell 29
MA cell 29

Fig. 10

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The Kruger National Park Rivers research programme

C Breen, M dent, J Jaganyi, B Madikizela , J Maganbeharie, A Ndlovu, J O'Keeffe, K Rogers, M Uys and F Venter

The Kruger National Park Rivers Research Programme is a co-operative undertaking by resource-use managers, funding agencies and researchers. It addresses the water quality and water quantity requirements of the natural environments of rivers, particularly those flowing through the Kruger National Park.

The Programme, envisioned at a workshop convened by the Department of Water Affairs in March 1987, was initiated in December 1988 jointly by the government Departments of Water Affairs and Environmental Affairs, the Foundation for Research Development (now National Research Foundation), the National Parks Board (now South African National Parks), the Water Research Commission and various research institutions and provincial nature conservation authorities.

There have been three phases. The fist can be broadly described as 'scientific research'. A comprehensive review of Phase I acknowledged the high quality of science and recommended that in the event of a second phase, management should be strengthened. Phase II was initiated in 1994 after preparation of a comprehensive Programme Description.

Recognition of this Focused Phase II on enhancement of predictive capabilities and contextualizing these within the management process so that decision-making could be supported.

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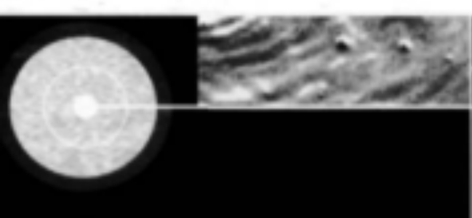

Water Research Commission
Private Bag X03, Gezina, 0031, South Africa
Tel: +27 12 330 0340, Fax: +27 12 331 2565
Web: http://www.wrc.org.za