Adaptive assessment and management of riverine ecosystems: The Crocodile/Elands River case study

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Abstract

The River Health Programme (RHP) is being designed to generate information regarding the ecological state of riverine ecosystems in South Africa. An adaptive assessment and management procedure is suggested as a means of linking the monitoring outcomes of the RHP with water resource management decisions. The potential of such a procedure is demonstrated, using data that have been collected, through the pilot application of the RHP, on the Crocodile and Elands Rivers, Mpumalanga.

In order to assess the collected data relative to a reference state, homogeneous river segments were identified. Each segment was classified in terms of its relative ecological integrity, based on three biological indicators (fish, benthic invertebrates, riparian vegetation). These assessments of current integrity were compared with management goals and quality objectives for the respective river segments. Finally, river segments were ranked in terms of priority for receiving management attention, and an example is given of formulating appropriate management actions for addressing a high priority need.

The systematic following of the step-wise procedure would facilitate and formalise the linking of data collection and assessment, the setting of management goals and quantifiable objectives, the selection of management options, and the monitoring of responses to chosen management actions.

Introduction

A national monitoring programme, that focuses on measuring and assessing the ecological state of riverine ecosystems, is being designed for South Africa. This programme, the River Health Programme (RHP), is developed with the overall goal of expanding the ecological basis of information on aquatic resources, in order to support the rational management of these systems (Roux, 1997).

For the RHP to become truly operational as a management information system, a step-wise procedure must be in place for linking the collected data and derived information with management actions. Therefore, in addition and parallel to protocols for site selection and indices with which to measure ecological condition, mechanisms must be developed for assessing the monitoring results in the context of management objectives, as well as for deciding on appropriate management activities.

To facilitate these parallel and interdependent initiatives, prototypes of both the monitoring methods and the step-wise procedure need to be tested in pilot exercises. By generating real data through pilot applications, a high degree of alignment and synergy between technical programme components can be encouraged. Such data are also essential for the construction of a systematic procedure for linking monitoring, assessment and management outputs.

Considerable attention has and is being given to the conceptual development and practical testing of the technical components of the RHP. Examples include the development of a protocol for the selection of monitoring sites (Eekhout et al., 1996), indices for assessing the condition of communities of fish (Kleynhans, 1999) and riparian vegetation (Kemper, 1998), as well as for establishing natural baseline conditions for aquatic invertebrates (Dallas, 1999). However, no formal procedure has been suggested for linking the information output of the programme with management decisions.

Note that the word procedure, as used in this paper, refers to a set of steps that needs to be performed in order to achieve a certain outcome. The outcome is to establish a closed loop between the monitoring, assessment and management of the ecological state of riverine ecosystems. Each step may consist of one or more protocols or methods.

This paper proposes a procedure which enables managers to respond to the results of the RHP. The procedure is demonstrated by applying existing data, obtained through pilot application of the RHP on the Crocodile and Elands Rivers (Mpumalanga). Emphasis is on the links between the different steps and the continuity provided by the overall procedure, rather than on the detail of protocols used within each step. Prototype outcomes of each step are, however, used for demonstrative purposes.

Background

The river health programme (RHP)

Design of the programme

The formal design of the RHP was initiated in 1994 by the Department of Water Affairs and Forestry (DWAF). The main purpose was for the programme to serve as a source of information regarding the overall ecological status of riverine ecosystems in South Africa. For this reason, the RHP essentially makes use of in-stream biological response monitoring (effects monitoring), in order to characterise the response of the aquatic environment to multiple disturbances. The rationale is that the integrity of the biota inhabiting the river provides a direct, holistic and integrated

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measure of the integrity of the river as a whole (Karr and Chu, 1997).

A phased approach was adopted for the design of the monitoring programme, to facilitate the formulation of a design framework, the conceptual development of the programme within that framework, and testing, demonstration and eventual implementation of the programme (Roux, 1997).

The objectives of the programme are to:

- measure, assess and report on the ecological state of aquatic ecosystems;
- detect and report on spatial and temporal trends in the ecological state of aquatic ecosystems; and
- identify and report on emerging problems regarding the ecological state of aquatic ecosystems in South Africa.

The concept of integrity, as developed for riverine biota (Karr et al., 1986) and for in-stream and riparian habitats (Kleynhans, 1996), is used as the basis for measuring and assessing the ecological state of aquatic ecosystems.

The conceptual design phase dealt with selecting and/or developing technical procedures, for example to select monitoring sites and ecological indicators, deciding on monitoring frequency and creating systems for the management of data and information. Communities of fish, aquatic invertebrates and riparian vegetation are the primary indicators used in the RHP. However, to provide a framework within which to interpret the biological results, some abiotic indicators (e.g. geomorphology, habitat, hydrology, water quality) have also been proposed. Measurement indices for some of these indicator groups have been developed, tested and are applied widely in South Africa, while others still need considerable development and testing (Uys et al., 1996).

Throughout its design, the RHP has been tailored in recognition of local capacity and resource availability. As a programme intended for national and long-term application, its technical specifications need to be sufficiently pragmatic to ensure the realisation of ongoing maintenance.

Implementation of the programme

The design of a monitoring programme *per se* will not provide the information required by resource managers. The design needs to be implemented, and the programme must be maintained and modified through ongoing learning, to match the evolving information needs of resource managers. Procedures, technical capabilities, infrastructures, political support as well as buy-in from stakeholders at large, are required to implement the programme. Many individuals and organisations may play a role in turning the design into an operational system which will allow the programme to achieve its objectives.

The third and current phase of the programme design revolves around providing broad guidelines to facilitate the implementation and maintenance of the programme. Issues that are receiving attention during this phase include: devising functional institutional arrangements; assessing and creating the required capabilities and capacities; instituting educational and training programmes; exploring and maximising funding options; and prototyping and demonstrating methods. Part of the institutional arrangements are that the Department of Environmental Affairs and Tourism (DEAT) and the Water Research Commission (WRC) have, together with the DWAF, become joint custodians of the programme at a national level. Provincial Champions and Provincial Implementation Teams are responsible for implementation initiatives at a provincial level.

In the Province of Mpumalanga, the provincial implementation initiative is being driven by the Mpumalanga Parks Board and the Kruger National Park. As part of the pilot application of the RHP on the main rivers of Mpumalanga, the first complete monitoring exercise of this nature took place on the Crocodile and Elands Rivers, during late 1996 and early 1997. The data generated through this exercise are used for demonstrative purposes in this paper.

The adaptive environmental assessment and management (AEAM) approach

The theory of adaptive environmental assessment and management

Managers of natural resources are confronted with the complexity of ecosystems, including long-term ecological processes, unpredictable natural disturbances and human influence. Even with the best available science, complete answers to all management questions will not be attainable. In fact, every change in environmental policy and management action presents a perturbation experiment with highly uncertain outcome. Thus, in no place can we claim to predict with absolute certainty either the ecological impact of cumulative stresses, or the efficacy of most measures aimed at regulating these stresses (Walters and Holling, 1990).

It follows that the management of ecosystems involves unpredictability and uncertainty. A given of modern living is that resource managers must make decisions despite incomplete information about how ecosystems function and react. They manage under uncertainties, which inevitably leads to some mistakes being made. The essential point is that dynamic resource management systems and policies are required to effectively react to our continually improving understanding of evolving ecosystem conditions; thereby providing flexibility for adapting to change and surprises (Holling, 1995).

The need for flexibility, in terms of ongoing learning and associated adaptation, in natural resource management led to the notion of AEAM (Holling, 1978). AEAM implies that successful ecosystem management depends on learning about the system while managing it.

In applying AEAM, resource management is essentially treated as an adaptive learning process where management activities themselves are viewed as the primary tools for experimentation. AEAM is an iterative process that includes collecting data, setting goals, modelling the effects of management options on ecological and social attributes, monitoring outcomes, and revising the management plan. When properly integrated, the process is continuous and cyclic; components of the adaptive management model evolve as information is gained and social and ecological systems change (Haney and Power, 1996).

A procedure for adaptive assessment and management of aquatic ecosystems

The concept of AEAM was used as the basis for developing a systematic procedure for responding to the monitoring results of the RHP (Fig. 1). The step-wise procedure links the collection and assessment of data through the RHP, in a structured and consistent way, with water resource management decisions. The overall goal of the procedure in this context is to facilitate environmentally sustainable development of riverine ecosystems at a high level, in line with the National Water Act (Act No 36 of 1998).

Effective implementation of the RHP design will provide for the ecosystem monitoring (data collection) (Fig. 1). The remainder of this paper is concerned with developing the links between monitoring and ecosystem assessment (information generation) and ecosystem management (making and execution of decisions).

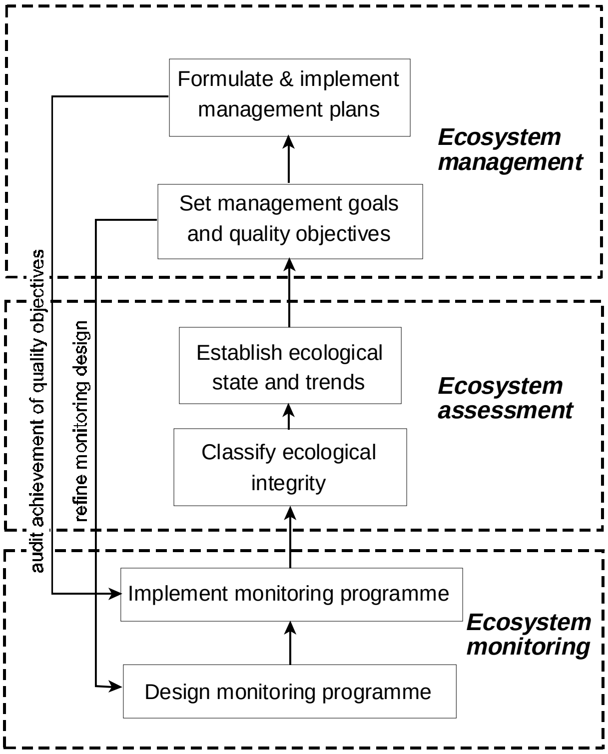

Figure 1
The AEAM procedure, as developed for application in the RHP context

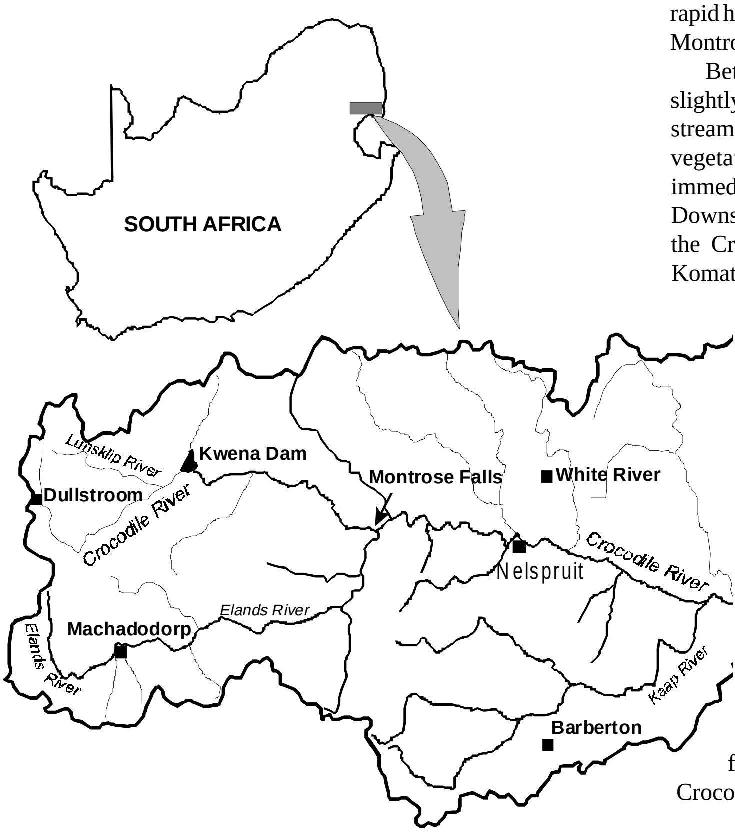

Figure 2
Map of the study area

The nature of the outputs required from, as well as the links between, individual steps shown in Fig. 1 are demonstrated through applying the RHP survey results from the Crocodile and Elands Rivers.

Study area and biological indices used

Study area

The Crocodile River is, from an ecological point of view, one of the most important rivers in the country. The river is characterised by a broad range of riverine habitats, ranging from cold mountain streams in the Drakensberg to the slow flowing warm waters where the river meanders through the Lowveld. As a result of the diverse habitats, the river is also one of the most biologically diverse systems in South Africa, with at least 49 fish species occurring here (*State of the Crocodile River*, 1998). Apart from its ecological importance, the Crocodile River is also one of the most economically productive catchments in the country (DWAF, 1995).

The Crocodile River catchment has an area of 10 440 km^2 (Fig. 2). The river rises at an altitude of approximately 2 000 m a.s.l. near Dullstroom in the Steenkampsberg Mountains. The upper catchment consists of steep-sided valleys, often with sharply defined cliff slopes on the eastern edge of the escarpment. From the escarpment, the Crocodile River levels out into the basin of the Kwena Dam. Downstream of Kwena Dam, the river winds along the valleys of the Drakensberg Mountains (Schoemanskloof) to Montrose Falls and the confluence of the Elands River.

The Elands River, a tributary of the Crocodile River, rises in a gently sloping Highveld zone near the town of Machadodorp. Downstream of its source, the Elands River has a steeper gradient for most of its length, and is characterised by exceptional riffle and rapid habitats. It joins the Crocodile River 2 km downstream of the Montrose Falls.

Between Montrose Falls and Nelspruit, the Crocodile River is slightly incised into a broad, flat-bottomed valley. Further downstream, steep-sided river banks are densely colonided with riparian vegetation and reedbeds, before the river flows through a gorge immediately upstream of the confluence with the Kaap River. Downstream of its confluence with the Kaap River, the gradient of the Crocodile River flattens out until its confluence with the Komati River at the town of Komatipoort. In this zone the Crocodile River forms meanders, incised into a wide sandy river bed. In other sections the river flows through multiple bedrock channels. From the town of Malelane and further downstream, the river also forms the southern boundary of the Kruger National Park.

Biological indices used

Indices were used to measure community attributes of fish, aquatic invertebrates and riparian vegetation on the Crocodile River.

Fish assemblage integrity index (FAII) - This index is based on a categorisation of a fish community according to an intolerance rating which takes into account trophic preference and specialisation, habitat preference and specialisation, requirement for flowing water during different life-stages, and association with habitats with unmodified water quality. Results of the FAII are expressed as a ratio of observed conditions versus condition that would have been expected in the absence of human impacts (Kleynhans, 1999).

South African Scoring System (SASS) - This index, based on the presence of families of aquatic macroinvertebrates and their perceived sensitivity to water quality changes, is currently in its fourth stage of development (Chutter, 1998). SASS has been tested and is used widely in South Africa as a biological index of water quality (e.g. Dallas, 1997 and Thirion, 1998). SASS results are expressed both as an index score (SASS score) and the average score per recorded taxon (ASPT value).

Riparian vegetation index (RVI) - This index is under development, and the prototype used for this survey represents a slight modification from the method developed by Kemper (1994). The RVI determines the status of riparian vegetation within river segments based on the qualitative assessment of a number of criteria (vegetation removal, cultivation, construction, inundation, erosion/sedimentation and exotic species) in the riparian zone.

Ecosystem assessment

The ecosystem assessment component of the AEAM framework deals with interpreting the data which were collected during monitoring (Fig. 1). In the context of the RHP, these assessments aim at expressing the degree of modification to the ecological integrity that exists in a particular section of a river.

The assessment component consists of two steps, namely to:

- classify ecological integrity - establish a reference classification for varying degrees of modification to the integrity of the ecosystem(s) to be assessed; and
- establish ecological state and trends - determine the present degree of modification to the integrity of each ecosystem in relation to the reference classification.

Classify ecological integrity

Demarcating riverine ecosystems

The biological and habitat information generated by the RHP allow the classification of riverine ecosystems, based on the degree of modification relative to natural benchmark conditions. The natural benchmark, per ecological indicator group, is defined as the set of conditions which can be expected in the absence of human impacts. This definition is compatible with the concept of ecological integrity (Kleynhans, 1996), and implies that benchmark conditions are specific to a particular riverine ecosystem. The benchmark condition does not imply a stable state, and should reflect natural variation over time.

The spatial scale selected for distinguishing between different riverine ecosystems will depend on the specifications of the monitoring programme of concern. In other words, two neighbouring pools in a river can be regarded as separate ecosystems, or two neighbouring river systems can be regarded as separate ecosystems. Results from the RHP are intended to provide insight into the relative degree of impairment of, or impact on, a section of a river as an ecological unit. The delineation of such homogeneous sections needs to be defined in a sound and systematic manner.

A multi-level hierarchical system is being developed for the typing of rivers in South Africa (DWAF, 1998; Kleynhans et al., 1998c; Kleynhans et al., 1998d; Louw, 1998). The principle of river typing is that rivers grouped together at a particular level of the hierarchy will be more similar to one another than to rivers of other types. This typing procedure was followed by Kleynhans et al. (1998b) to group the streams of the Crocodile River catchment to the second hierarchical level. Within these river types, a further segmentation of the river channel was based on broad geomorphological characteristics of the river (Fig. 3 and Table 1). These geomorphological river segments form ecological management units for which natural benchmark conditions can be defined.

Establish reference classification

Natural benchmark conditions were derived for each of the biological indicator groups for each identified river segment. Benchmark conditions for the FAII were based on a combination of historical evidence of the distribution of fish species as well as professional

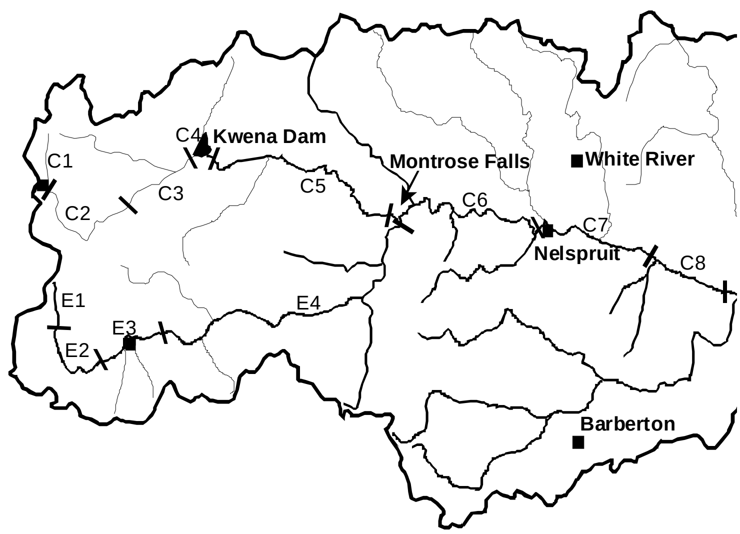

Figure 3
Map indicating preliminary geomorphological segments for the Crocodile and Elands Rivers

TABLE 1 BROAD DESCRIPTION OF THE RIVER SEGMENTS IDENTIFIED FOR THE CROCODILE AND ELANDS RIVERS	
River segment	**General characteristics**
Crocodile River	
C1	1 to 2 m wide; small rocky pools with riffles; steep slope; wetland and grassland dominated
C2	5 to 10 m wide; rocky pools and runs with occasional riffles and some small waterfalls; steep slope; grassland with scattered woody component and scrubs
C3	10 to 15 m wide; rocky pools and runs with occasional riffles; steep slope; change from afromontane forest to grassland and woody component to grassland
C4	Kwena Dam; grassland dominant with woody component
C5	15 to 20 m wide; large rocky pools interspersed abundantly with riffles and rapids; steep slope; riparian forest
C6	20 to 30 m wide; large rocky pools and runs with occasional rapids; riffles rare; moderate slope; change from mountain riparian forest to foothill riparian forest
C7	30 to 40 m wide; large rocky pools and runs with occasional rapids; riffles very rare; moderate slope; change from mountain riparian forest to anastomosing lowveld riparian forest with reeds
C8	20 to 30 m wide; rocky pools and runs with cobbles and boulders, rapids and riffles abundant; steep slope; gorge riparian forest
C9	30 to 40 m wide; rocky and sandy pools and runs with riffles and rapids; moderate slope; lowveld riparian forest
C10	40 to 50 m wide; mostly large sandy pools with occasional rapids; riffles very scarce; gentle slope; lowveld riparian forest
C11	40 to 50 m wide; mostly large sandy pools with occasional rapids; riffles very scarce; gentle slope; lowveld basalt riparian thicket (basalt bedrock limited)
C12	40 to 50 m wide; mostly large sandy pools with occasional rapids; riffles very scarce; gentle slope; Lebombo riparian thicket (rhyolite bedrock limited)
Elands River	
E1	1 to 2 m wide; small pools; gentle slope; grassland
E2	1 to 2 m wide; small pools with occasional riffles; moderate slope; grassland with scattered woody component
E3	5 to 15 m wide; large rocky pools with riffles and rapids; moderate to steep slope; grassland with scattered woody component
E4	15 to 20 m wide; large rocky pools with abundant riffles and rapids; steep slope; change from mountain riparian forest to foothill riparian forest to mountain riparian forest

judgement. The best SASS index scores, usually obtained at the least impacted site, were regarded as the benchmarks for particular segments. This was both for the SASS index score and the average score per taxon (ASPT value). Expert opinion was used to define the RVI for each segment.

The natural benchmark conditions, as determined for each biological index for each river segment, were used for calibrating the degree of modification to ecological integrity. A six class division was used, to be compatible with other complementary initiatives, for example a classification system for habitat integrity (Kleynhans, 1996) as well as for the protection of water resources in South Africa (DWAF, 1998). In the classification scheme for ecological integrity of riverine ecosystems, Class A represents the natural benchmark state and Class F a state of critical modification (Table 2). These classes will be referred to as river integrity classes (RICs).

The way in which the divisions between the different RICs are defined (percentage cut-offs in Table 2), is based on professional judgement and may differ for the different biological indicator groups. A classification scheme (Table 2) allows for standardisation of the assessment process to a degree where different people using the same measured data will consistently arrive at the same RIC. In some instances, this statement will be an oversimplification, as expert judgement and system specific knowledge often form part of the assessment rules for the respective ecological indicator groups.

The rules defining the ranges within different classes (Table 2) need not change between river segments, but the benchmark values will change to reflect the natural variation in ecological parameters over space and time. For example, a benchmark value for the SASS index score may be 200 for one river segment and 70 for a river segment in another part of the country. Similarly, the benchmark ASPT values for the SASS index may differ between the mentioned segments. These benchmark values will form the basis for translating SASS data, measured at any particular point in time at the mentioned segments, into RICs.

Establish ecological state and trends

The present ecological status of the respective river segments was defined by applying the results for the biological indices, obtained during the survey of the Crocodile and Elands Rivers, to the ecological integrity classification scheme (Table 2). The present ecological state for each river segment was thus defined as an integrity class per biological indicator group (Table 3).

A low monitoring frequency is prescribed by the national RHP objectives. This frequency varies among the different biological indicators in accordance with differences in life-cycle durations and associated response times. Monitoring of fish and riparian vegetation is likely to take place once in three years, and the invertebrates once per year (Uys et al., 1996). Over time, it would be possible to detect temporal trends for the relevant river segments and biological indicator group(s). The results (Table 3) clearly show spatial trends in the ecological state/integrity of river segments.

Table 2 **The Classification of Ecological Integrity of Riverine Ecosystems Used for the Assessment of RHP Results**				
River integrity class (RIC)	**FAII as % of natural benchmark (Kleynhans, 1999)**	**SASS as % of natural benchmark (Thirion, 1998)**		**RVI as % of natural benchmark (Kemper, 1994)**
		SASS score	**ASPT value**	
A - No measurable modification	≥ 90	90 70 to 89	variable ≥ 90	≥ 90
B - Largely unmodified	80 to 89	80 to 89 70 to 79	<90 80 to 89	80 to 89
C - Moderately modified	60 to 79	60 to 79 70 to 79	variable <80	60 to 79
D - Largely modified	40 to 59	40 to 59	variable	40 to 59
E - Seriously modified	20 to 39	20 to 39	variable	20 to 39
F - Critically modified	0 to 19	0 to 19	variable	0 to 19

Table 3 **Present Ecological State, Expressed as an Integrity Class, of the River Segments Identified for the Crocodile and Elands Rivers**			
River segment	**Riverintegrity class (RIC)**		
	FAII	**SASS**	**RVI**
Crocodile River			
C1	A	B	B
C2	B	A	C
C3	B	A	D
C4	NA	NA	D
C5	B	B	C
C6	C	B	C
C7	D	D	C
C8	C	C	C
C9	C	C	D
C10	C	B	D
C11	C	D	D
C12	C	A	D
Elands River			
E1	NA	NA	D
E2	A	A	D
E3	A	A	D
E4	A	A	C
NA - not available			

Ecosystem management

The ultimate aim of accurate ecosystem assessment is the dynamic and effective management of water resources. At the high level of the AEAM procedure, resource management consists of two steps, namely firstly to set management goals and associated quality objectives, and secondly to make management decisions. Management goals are viewed as broad qualitative statements which reflect some foresight and commitment from policy-makers and managers, and incorporate societal values, as to the condition in which an ecosystem should be maintained. In order to give operational meaning to these goals, they should be translatable into measurable scientific end-points, referred to here as quality objectives. Where the goals consist of a qualitative vision for the river, the quality objectives are quantitative values or ranges of values that can be used to monitor, manage for and audit attainment of the goals.

In the context of the RHP, the management goals and quality objectives define desired characteristics of ecological values to be protected. The management goal is the same as the "desired state" of an ecosystem, as referred to by some authors (e.g. Rogers and Bestbier, 1997). Management decisions refer to determining the means for achieving the management goals. In other words, appropriate management plans must be formulated and implemented.

The separate river segments are suggested as ecological management units. Therefore, a management goal and quality objectives must be determined and a management strategy must be formulated for each of the identified river segments.

Set ecosystem management goals and quality objectives

Management goals

In the assessment component of the AEAM procedure (Fig. 1), degrees of ecological impairment have been quantified per river segment or aquatic ecosystem. Ecological management goals must be set to judge the acceptability of these levels of impairment. However, the quantification of ecological goals for aquatic ecosystems is both technically complex and politically controversial. Such goals need to be ecologically sound and sustainable, but at the same time allow for some desired degree of socio-economic development.

The decision on the ecological management goal for a particular aquatic ecosystem requires the achievement of a balance between three aspects:

- The ecological importance and sensitivity of the resource, which includes biodiversity, rarity, uniqueness and fragility from habitat, species and community perspectives. The intrinsic ecological value of the resource and its importance to the functioning of neighbouring ecosystems are the main concerns.

TABLE 4 ECOSYSTEM MANAGEMENT GOALS FOR THE CROCODILE AND ELANDS RIVER SEGMENTS	
River segment	**Ecological management goals**
Crocodile River	
C1	A
C2	B
C3	B
C4	B
C5	B
C6	B
C7	C
C8	B
C9	B
C10	A
C11	A
C12	A
Elands River	
E1	C
E2	B
E3	B
E4	A

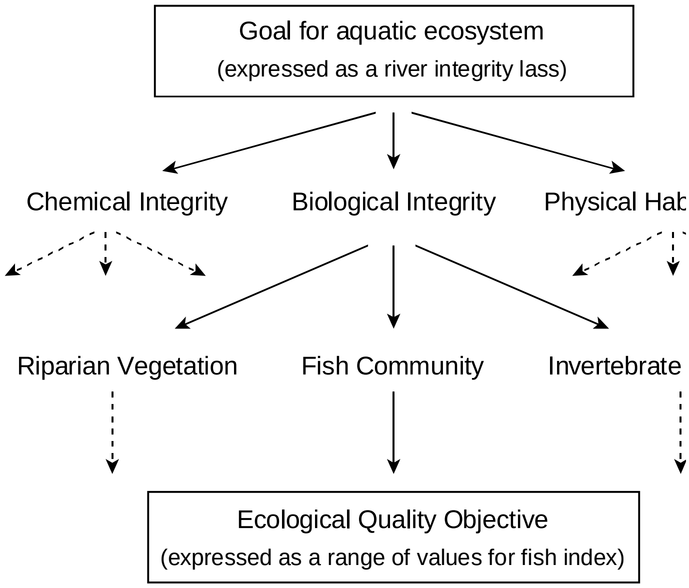

Figure 4
Integrating human values and scientific endpoints in setting visionary management goals and measurable quality objectives for riverine ecosystems

- The strategic importance of the resource for human use, which refers to the water requirement for various economic sectors (such as agriculture, industry and mining), and for basic human and social needs (such as recreation, tourism and religion).
- The current as well as reference ecological integrity of the resource. The availability of quantitative or qualitative information on the reference biological integrity and the current biological integrity of a river will contribute towards setting realistic and ecologically sound management goals.

Consideration of all of the above aspects should ideally be part of the process of goal setting. The outcome would be a negotiated decision, where human values and stakeholder participation would have played important roles. Such a consultative management process has been developed to support the conservation policy of the Kruger National Park (Rogers and Bestbier, 1997). This methodology may need some modification before it can be applied in the context of the national Water Act.

To demonstrate the overall AEAM procedure, the ecological importance and sensitivity of the respective ecosystems were considered in deriving broad ecological management goals for the Crocodile and Elands Rivers. The strategic importance of the resource for human use was not considered, as such an assessment has not been done for the rivers of concern and could not be undertaken within the scope of this study.

Ecological importance of a river is an expression of its importance to the maintenance of ecological diversity and functioning on local and wider scales (Kleynhans et al., 1998a). Ecological sensitivity (or fragility) refers to the system's ability to tolerate disturbance and its capacity to recover from disturbance once it has occurred (resilience) (Resh et al., 1988 and Milner, 1994).

Kleynhans et al. (1998a) suggest the following ecological aspects be considered as the basis for the estimation of ecological importance and sensitivity:

- The presence of riparian and in-stream biota, in terms of:
  - rare and endangered species
  - unique (endemic, isolated, etc.) species and communities
  - intolerant species
  - overall species diversity and richness.
- The presence of riparian and in-stream habitats, in terms of:
  - diversity of types
  - providing refuge areas
  - providing connectivity between neighbouring reaches or systems, i.e. providing a migration route or corridor for species.
- The presence of conservation or natural areas, such as national parks, nature reserves and wilderness areas.

A scoring system, which integrates the relative importance of the above issues, has been developed by Kleynhans et al. (1998a). This system is intended as a guideline for the professional judgement of relevant specialists familiar with the study area. As the authors represent extensive experience of the relevant ecological attributes of the Crocodile River system, their combined judgement was deemed sufficient to provide a valid outcome in terms of the ecological importance and sensitivity ratings for the identified river segments.

The ecological importance and sensitivity scoring system was tailored to present the results as one of six classes (A to F). The class obtained in the present evaluation was considered to be equivalent to the ecological management goal for the relevant segment. The goals for the Crocodile and Elands Rivers are presented in Table 4.

Ecological quality objectives

Whereas the management goal reflects the ecological values that we seek to protect, these values need to be translated into measurable ecological quality objectives (EQOs) in order to become operational. Once consensus is reached on a management goal for a particular river segment, and if this goal can be expressed in terms of a specific RIC (Table 2), then EQOs can be allocated per ecological indicator group. Thus, the range of index scores coinciding with the desired integrity class for each biological indicator group becomes measurable and auditable quality objectives. Figure 4 shows how such a goal statement can be translated into EQOs.

A comparison of the set management goal and the determined current RIC of each river segment will indicate which EQOs are met and where management action is required to ameliorate undesirable conditions. However, this comparison will not always be straightforward and simple. In instances where the RIC differs among the indicator groups, an expert system may have to guide decisions regarding compliance with the set management goal. Such rules are currently being developed for the implementation of resource-directed measures for the protection of aquatic ecosystems, as specified under the National Water Act (DWAF, 1998), and fall outside the scope of this paper.

Formulate and implement management plans

Ranking ecosystems for management action

Threats to achieving or maintaining the set goal for a river segment may vary in type, severity, extent and imminence. Amidst this variability, resource managers need to rank ecosystems at risk in order to set priorities for management action. Such prioritisation would allow them to focus their resources at areas where the need is most urgent.

There are three basic types of methods for ranking ecosystems at risk; negotiated consensus, voting and formulae (EPA, 1993 as cited in Gonzalez, 1996). Gonzalez (1996) proposes a three-dimensional ranking system which makes use of negotiated consensus along with a simple additive formula. This relatively simple ranking system consists of the following three components:

- category of threat;
- level or class of threat; and
- distance from desired future condition (i.e. distance from the management goal).

A description of how each of these components contribute to the ranking system, as modified from Gonzalez (1996), follows.

- ***Category of threat to ecosystems****:* Threat to any ecosystem of concern can be grouped into three broad categories:
  - Category 1 Ecosystem degradation - occurs mainly through pollution, but could also be from selective removal of species (e.g. overfishing).
  - Category 2 Alteration - major physical changes (such as dredging, water diversion, impounding) and major removal of species (i.e. extinction).
  - Category 3 Removal - highest level of alteration (e.g. destruction of wetlands due to urbanisation, conversion of forest to cropland, etc.).

- ***Level of threat to ecosystems****:* Four levels of threat to ecosystems are proposed:
  - Level 1 Without intervention, the ecosystem's integrity will be largely unchanged three to five years from now.
  - Level 2 Without intervention, ecosystem status will have declined somewhat three to five years from now [the ecosystem is likely to drop one integrity class].
  - Level 3 Without intervention, ecosystem status will have dramatically declined, perhaps resulting in ecosystem disappearance three to five years from now [the ecosystem is likely to drop two integrity classes].
  - Level 4 Collapse or disappearance of the ecosystem is imminent in less than three years [the ecosystem is likely to drop three integrity classes].

- ***Distance from the management goal****:* Four "distances" from the management goal can be distinguished:
  - Distance 1 In the same RIC as the management goal.
  - Distance 2 One RIC away from the goal.
  - Distance 3 Two RICs away from the goal.
  - Distance 4 Three RICs away from the goal.

Gonzalez (1996) suggests that ecosystems could be prioritised for receiving management action, by giving numeric weights to the different categories, levels and distances and summing them. Decisions on the category of threat and level of threat, could be made by an expert panel consisting of scientists, conservationists, resource managers and stakeholder groups. The qualitative determinations would represent a negotiated consensus of expert judgement based on both qualitative and quantitative information (Gonzalez, 1996).

The distance from that management goal, however, is a more objective assessment. It could be determined mechanistically for each river segment using the river integrity classification system (Table 2), the present RICs (Table 3) and the management goals/classes (Table 4). To demonstrate the concept of ranking ecosystems, only the distance component was considered for ranking segments of the Crocodile and Elands Rivers for management action. The following simple formula was used:

$$D = RIC_{Goal} - (RIC_{FAII} + RIC_{SASS} + RIC_{RVI} \ldots\ RIC_{i})/n \qquad (1)$$

where:

D is the distance from the management goal
RIC_{Goal} is the management goal expressed as a RIC (Table 2)
RIC_{FAII} is the current RIC according to the FAII
RIC_{SASS} is the current RIC according to the SASS
RIC_{RVI} is the current RIC according to the RVI
n is the number of ecological indices for which a current RIC has been determined

and where Class A equals 6 and Class F equals 1 numeric unit.

Formula (1) is suggested strictly as a mechanism for the ranking of river segments in terms of their need for receiving management attention. It should not be used to assess compliance with a set goal, as a wider set of variables needs to be considered for this (explained under **Ecological Quality Objectives**). Similarly, it can also not be used to argue the case that the river has additional capacity that can be used for development (e.g. in cases where the current RIC is higher than the management goal).

The distance values (Table 5) provide the outcome of applying Formula (1) to the present ecological state (Table 3) and management goal (Table 4). In practice, the response of managers to these distance values depends on the philosophical debate of whether river segments which shows the highest or lowest distance values should receive priority attention. It could be argued that the first priority is to maintain the integrity of those segments already meeting the management goal; or that the segments that deviate most from the goal should receive priority to improve their state. To demonstrate the concept of prioritisation, it is assumed that the larger the numeric value the more urgent the need for management action in a specific segment.

TABLE 5
THE DISTANCE BETWEEN THE ECOLOGICAL MANAGEMENT GOALS AND CURRENT ECOLOGICAL STATE FOR EACH RIVER SEGMENT, AS DETERMINED BY EQ. (1) AND WHERE ZERO IS THE CLOSEST AND FIVE THE FURTHEST

Riverine segment	Distance from management goal
Crocodile River	
C1	0.7
C2	0.0
C3	0.3
C4	2.0
C5	0.3
C6	0.7
C7	0.7
C8	1.0
C9	1.3
C10	2.0
C11	2.7
C12	1.7
Elands River	
E1	1.0
E2	0.0
E3	0.0
E4	0.7

TABLE 6
STRESSORS POTENTIALLY RESPONSIBLE FOR THE UNDESIRABLE ECOLOGICAL CONDITION IN RIVER SEGMENT C11

Biological index	Stressors
FAII	- Primarily a flow-related problem, due to the regulation of discharges from Kwena Dam and excessive water abstraction for irrigation purposes in the middle and lower parts of the Crocodile River. This results in habitat loss which adversely impacts on the fish community in this segment (particularly during periods of drought). - Water quality deterioration, mainly as result of irrigation return flows and associated nutrient enrichment and algal growth. - Presence of exotic aquatic macrophytes, mainly hyacinth (*Eichhornia crassipes*), resulting in habitat alterations (especially during low flows).
SASS	- Water quality deterioration, mainly as a result of irrigation return flows and associated nutrient enrichment and algal growth. - Loss of stable riffle habitat at some long-term monitoring sites due to sedimentation and sand cover.
RVI	- Vegetation removal on the southern bank, due to the construction of roads, pump houses, tourist lodges, etc.

It is possible to devise management guidelines based on the outcome of Table 5. For example, a distance above one implies a need for management action, above two a serious need and above three a critical need. A distance of four or higher would probably imply that management intervention in the form of ecological restoration is required. Although these cut-offs may seem arbitrary, the idea behind AEAM is to have and apply preliminary rules which can be improved as experience and knowledge is gained. In other words, not to wait with management action until complete certainty is obtained, as such a situation may never materialise. Instead, management action becomes part of the process of gaining evidence that would allow managers to shape and improve prototype rules in an ongoing fashion.

Where a current RIC for only one indicator was available (e.g. segment E1), the result should be viewed with lower confidence than where the results of three indicators were used. The use of more ecological indicators, for example the inclusion of the Index of Habitat Integrity (Kleynhans, 1996), would allow a more comprehensive assessment of ecosystem state and more confidence could be linked to the outcome.

Formulate management actions

Once ecosystems have been priority ranked, the actual management plans for high ranking segments need to be established. In the example used here, segment C11 ranked worst. By referring back to the original data collected, and observations during the field survey, it will often be possible to identify the likely stressors that resulted in the high ranking. However, this may not always be obvious, and additional and more intense monitoring and observation may be required to establish such links for the river segment(s) of concern.

The stressors that could be linked to the undesirable ecological condition of segment C11 are presented in Table 6.

Based on the knowledge of the main stressors which are having an effect on the integrity of segment C11 (Table 6), it is relatively simple to recommend management options which would assist improvement of ecological conditions towards the management goal for this segment. The authors felt that three broad management options would result in an improvement over time:

- The determination of the in-stream flow requirement (King and Louw, 1998) in order to meet the management goals at the lower parts of the Crocodile River (segments C10 to C12), and associated operational management of water releases from Kwena Dam.
- Restoration and/or proper management of the riparian zone on the southern bank of segments C10 to C12, to form an effective buffer area against erosion and leaching of nutrients from irrigation activities.
- The control of water hyacinth.

The example of segment C11 is relatively straightforward. However, it is possible that multiple or alternative management options could be identified for another situation. Here another prioritisation procedure will be required, as most often more than one management activity may result in a similar effect. Haney and Power (1996) suggest an implementation index to prioritise various management options on the basis of their political and technical feasibility and perceived efficacy.

They assigned a rating to each management option based on political feasibility (PF), technical feasibility (TF) and efficacy (E), with a value of 1 being the least acceptable and 5 being the most acceptable. These values were combined to yield an implementation index (I), where:

$$I = (PF + TF) (E) \quad (2)$$

By applying the implementation index to all possible options, the most feasible and efficient management option can be determined in a fairly structured way.

The only way to verify that the chosen management plans result in the specified management goal, is by ongoing monitoring of those end-points (quality objectives) with which the goal is being described. This feedback to ongoing monitoring closes the loop between monitoring and management (Fig. 1). Monitoring data would then show whether chosen management actions result in progress towards management goals (Haney and Power, 1996). Modifications to the monitoring design may be required to properly audit performance relative to specified goals (Fig. 1). This would be particularly relevant when additional management actions or modified goals are suggested, or when new or refined relationships between stressors and environmental responses emerge.

To truly audit the adaptive relationship between a monitoring design and the setting of management goals, the AEAM system needs to be operational for a number of years. As the RHP does not provide such an example, the feedback from management to monitoring discussed above is hypothetical.

Discussion

The output of monitoring programmes such as the RHP must be used, at national, provincial and local levels of responsibility, in the management of aquatic ecosystems in Southern Africa. As it stands, the RHP provides the methodology to monitor changes in the ecological state of aquatic ecosystems, but not a framework for responding to the results. In the absence of such a framework, the RHP will have little further influence on how its results enter the management arena, if at all.

The AEAM model proposed in this paper is an attempt to formalise the dependancies between monitoring, assessment and management of aquatic ecosystems. It provides a systematic procedure which links the collection and assessment of biological data, the setting of goals and quantifiable objectives for managing the integrity of rivers, and the prioritisation of management actions. The balance between the protection and utilisation of aquatic ecosystems can be negotiated and hopefully optimised by following this iterative cycle, while also focussing on continuous improvement of the component protocols (Fig. 1).

Lessons from the development of this AEAM framework can be summarised as follows:

- The AEAM model ensures that recognition is given to the need for ongoing learning and adaptation. No prototype assessment method or management decision is ever the ultimate, but just the best that is available for now. Commitment to the AEAM process will avoid a situation where complacency with the familiar is an obstacle to future improvement of ecosystem monitoring, assessment and management.
- The AEAM procedure provides for the semi-quantitative assessment of the overall response of aquatic ecosystems to cumulative disturbances, in relation to both a natural benchmark condition and ecological management goals. Such assessments facilitate measurement of goal achievement, deciding on management actions and auditing management performance.
- The higher the number of ecological indicators used in the RHP, the more comprehensive an assessment of ecosystem condition will be possible, and the more confidence could be linked to resulting management decisions.
- The strong emphasis in the AEAM procedure on the results obtained through the various ecological indices, may drive a behaviour where the respective index scores become the sole management focus and where the holistic ecosystem perspective is diluted. It should be stressed that these ecological indices, although orders of magnitude more relevant than measuring only chemical concentrations, are still surrogate measures of ecosystem condition.
- The classification and rating techniques built into the AEAM framework would ensure a high degree of standardisation in the processing of RHP data. However, as professional judgement and system-specific knowledge are required inputs to certain components, absolute standardisation cannot be guaranteed - nor is this absolute rigidity necessarily desirable. Variability in the outcomes obtained from applying the AEAM procedure can only be limited by increasing the exposure of technical specialists and managers to the procedure.
- Although a consensus goal is not a prerequisite for making management decisions, a goal-oriented approach to resource management has the following advantages:
  - A defined goal provides the platform for strategic or proactive management, whereas the absence of a goal often encourages a wait-and-see approach and reactive management.
  - Measurable goals will allow an audit of management performance, which is in line with the greater emphasis on accountability of the custodians of natural resources.
  - Stated goals will increase transparency and encourage participation to incorporate the desires and expectations of more stakeholders.
  - The process of goal setting, if done in a transparent and participatory way, will acknowledge and consider the value systems of society.
  - The process of defining a goal will result in continuity regarding the rationale behind decision-making.
- Conceptualising the entire AEAM procedure provides an important perspective for the ongoing development and improvement of the individual protocols of which it is composed. By developing the process and its links in parallel with the separate technical components, improvement and functionality achieved over time can be optimised.
- The principles of the AEAM procedure are sufficiently generic to be applicable to other response monitoring programmes focussing on rivers and other natural resources. The national RHP is concerned with relatively coarse changes in the ecological status of rivers and river reaches over long time periods. A monitoring programme focussing on the consequences of a certain type of impact (cause-effect relationship) in one part of a catchment may employ more detailed biological indices at a higher sampling frequency. More specific management direction would flow from such a programme. Lastly, a programme designed to assess the local effects of a site-specific stressor may be based on biotoxicological assays. An example of such a programme is to monitor the response of aquatic species to an effluent discharge, where management actions may relate to a specific constituent of the effluent. A challenge would be to interlink the response frameworks of monitoring programmes with national, regional and local objectives in a complementary fashion and thus coming close to covering all spatial and

temporal scales relevant in the management of aquatic ecosystems.

- It is acknowledged that the setting of ecological management goals and the identification of management options would not automatically result in the implementation of management actions (Walters, 1997). These goals need to be institutionalised to ensure maintenance of the AEAM procedure (Rogers and Bestbier, 1997; Rogers, 1998). When institutionalising goals, one needs to address aspects of responsibilities, timeframes, required capacities, etc., relevant to the various institutions mandated with aquatic ecosystem management.

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