# How well has biophysical research served the needs of water resource management? Lessons from the Sabie-Sand catchment

**E. van Wyk[a*], B.W. van Wilgen[b] and D.J. Roux[a]**

**Since the era of great water engineering works in South Africa, there has been a major shift in the thinking and approach to water resources management. Previous focus on water supply has been replaced by demand management initiatives and the recognition that aquatic ecosystems require protection in order to provide goods and services to people. These paradigm shifts are now reflected in the legislation that governs the management and protection of natural resources, as well as in the management frameworks proposed for integrated water resource management. The fundamental changes in the approach to water resource management warrant a critical evaluation of the information generated by past research and of the relevance of this activity and associated knowledge generation, given the new management needs. This paper reviews historical research initiatives in the Sabie-Sand catchment and investigates the extent to which they have generated the kind of information that is required by current management approaches. We show that all of the research initiatives provide useful information at different temporal and spatial scales, but that there are conspicuous gaps in the research framework. Management in the Sabie-Sand catchment will benefit from greater focus on integrative, interdisciplinary research and on the ecology of restoring degraded land and water resources. Research initiatives need to make better use of opportunities for capacity building and to advance understanding of the interface between biophysical and social research, given the requirement for research to be part of the country's social transformation processes. It is hoped that the kind of evaluation provided by this paper will be used elsewhere to identify knowledge gaps in the framework for water resource research and, in doing so, enable decision-makers to direct future research investment more effectively.**

[a]CSIR Division of Water, Environment and Forestry Technology, P.O. Box 395, Pretoria, 0001 South Africa.
[b]CSIR Division of Water, Environment and Forestry Technology, P.O. Box 320, Stellenbosch, 7599 South Africa.
*Author for correspondence. E-mail: evwyk@csir.co.za

For most of the 20th century, water resource management in South Africa focused on supplying water to a growing population.[1,2] The emphasis on supply as the main component of water management followed a world trend characterized by the construction of large dams and other regulatory structures designed to meet growing demands on water resources. (Most dams in South Africa were built between 1930 and the mid-1970s.[3]) During the last two decades, South Africa began to run out of suitable sites for dam construction, but the population (and water demand) continued to grow. At about the same time, the concept of an 'ecological reserve' matured. This concept is based on the recognition that rivers require a certain amount of water to maintain a healthy aquatic system,[4,5] and its capacity to deliver goods and services to people.[2] As the paradigm shifted increasingly from one of water supply to water resource protection and water demand management, it became clear that new approaches for the overall management of water resources were required.

The need for new approaches and principles for resource management had a significant impact on the development of new policies in South Africa, and these principles are now embodied in the constitution and other legislation governing the management of natural resources. These are mainly the Department of Water Affairs and Forestry's (DWAF's) National Water Act (NWA, Act no. 36 of 1998) and the Department of Environmental Affairs and Tourism's (DEAT's) National Environmental Management Act (NEMA, Act no. 107 of 1998). Several principles in these acts are fundamentally different from previous legislation, such as the commitment to more equitable and sustainable management and use of water and other natural resources. Legislation therefore requires management practices that are different from those of the past.

The majority of principles in the NWA and NEMA that are relevant to biophysical research and management show considerable synergy. They include the need to consider the effects of various temporal and spatial scales of management on the biophysical responses within a catchment, and the recognition that greater integration is required in biophysical research. Legislation requires more focused efforts to meet international obligations and the adoption of adaptive management processes that will enhance our ability to predict biophysical response to management activities. The Water Act in addition requires that water resources management functions be delegated to the regional level as far as possible through the establishment of catchment management agencies (CMAs).

The changes in thinking and approaches to resource management reflected in the recently revised legislation means that the knowledge required to support these management approaches has also changed. In the past, research on the management of catchments and rivers was driven by sectoral needs (for example, the supply of water to meet demand, nature conservation, or forestry), or was largely discipline-specific, with engineers, terrestrial ecologists and aquatic scientists pursuing their research objectives separately. Recently, there have been notable exceptions. For example, the Kruger National Park Rivers Research Programme was a collaborative effort by resource managers, funding agencies and researchers.[6] However, management would benefit from a critical review of current and past research and the degree to which it will serve the new approach. We have chosen the Sabie-Sand catchment as a basis for this review, in light of the variety of research projects that have been conducted there, and a history of joint effort by researchers and resource managers to overcome water resource management challenges. These features provide an opportunity to learn from a rich collection of past research and management experience.

The objective of this paper is to provide an account of current information demands concerning the management of water resources, and an investigation of the degree to which historical research will provide the information necessary to support current management requirements. This process is used to identify gaps in the 'knowledge supply' provided by historical research, which, in turn, can be useful in guiding future research investment.

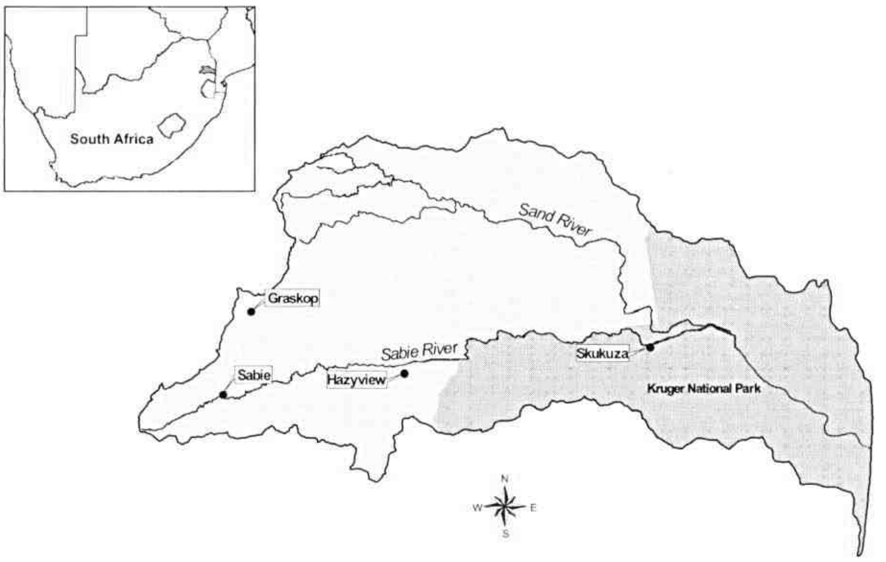


**Fig.1**. Location of the Sabie-Sand catchment in South Africa. The Sabie River extends into Mozambique at the eastern extremity of the catchment.

## The study area

The Sabie-Sand catchment (6308 km$^2$) is located in the northeastern part of South Africa (Fig. 1). It falls within the Mpumalanga and Northern provinces and forms part of the Inkomati River primary drainage region. The Sabie and its main tributary, the Sand River, have their origins in the mountainous western escarpment region of the catchment at an altitude of 2130 m above sea level. From here, the river drops rapidly to 234 m above sea level at the confluence of the Sabie and Sand rivers, some 125 km to the east. The Sabie River then flows for another 50 km through the Kruger National Park before it enters Mozambique. Mean annual rainfall in the catchment ranges from 1500 mm on the escarpment to 600 mm at the lower altitudes. Mean annual runoff is 762 million m$^3$, of which more than 90% originates in the headwater region of the catchment.[7] The major forms of land use include conservation (49% of the area), communal lands (a mixture of informal agriculture and urban development, 29%), commercial forestry (18%), and formal agriculture (4%).[8]

The 1991 population estimate for the five magisterial districts that fall partly or completely within the catchment boundaries was 840 000, with an overall density of 48 persons/km$^2$. Density distribution varies from 404 persons/km$^2$ in the Nzikazi district to 3 persons/km$^2$ in the Pilgrim's Rest district; population growth rates vary from –4.3% (White River) to 9.7% (Mapumaleng). Approximately 20% of the total labour force is unemployed and education levels are low, with 27% of the labour force having no schooling and 29% having only primary level education.[9]

## Historical research

We have identified 13 research initiatives relevant to the management of rivers and other natural resources in the Sabie-Sand catchment (Table 1). Past imperatives called for sector- or discipline-specific research projects, but there has already been a large degree of integration by researchers in the projects identified. Scientists have thus taken the lead in collaborating and anticipating future needs, and this is reflected in projects such as the Kruger National Park Rivers Research Programme, the River Health Programme, the land cover project and cumulative effects assessment. For example, the land cover project was a cooperative initiative that was supported by the CSIR, the Department of Agriculture, DEAT, DWAF and the South African National Defence Force. The Working for Water Programme, and the alien plant biocontrol research that supports it, involves contributions from several government departments and the private sector. A good start has thus been made towards integrating the contributions of various role-players to meeting the needs of sustainable resource management and protection.

Table 1 also shows that research traditionally focused on certain areas of natural resource management, while others received relatively little attention. Forest hydrology, alien plant concerns, and conservation interests, in particular, have been well served. As a result, our understanding of the concerns and impacts associated with these areas of resource management is relatively advanced. Forestry research offers a good example. Research on the hydrological effects of forestry has spanned several decades. By contrast, very little research has been done on the hydrological consequences of other forms of land use, which leaves managers and policy-makers unable to make informed decisions about land use from a biophysical perspective. Research focus on a particular area has left gaps in knowledge about the impacts of other areas such as agriculture and industry on integrated catchment management. This may be expected in the Sabie-Sand area, where agriculture and industry are not extensive, but the relatively heavy research investment in certain areas of land and resource use is true also for other areas in the country. Research projects have also tended to focus on resource use and impacts rather than protection and management for overall sustainability.

Previous policies did not require an integrated approach to research and management of natural resources. Past research has thus been proactive in terms of integrating disciplines to generate more integrated solutions supportive of catchment management. But, the imperatives brought about by the new legislation will require even further integration at higher levels. For example, none of the research initiatives explicitly addressed the links between terrestrial and aquatic ecosystems (although the land care initiative produced many recommendations in this regard, and the cumulative effects assessment produced a framework for addressing the effects of terrestrial activities on aquatic systems). With a few exceptions, there has been limited consultation with the majority of the population in the catchment, and the needs of Mozambique downstream are not explicitly catered for.

## Demands for information to be provided by research

Recent demands for research-based water resource management information has come mainly from two sources, namely the departments of Water Affairs and Forestry, and of Environmental Affairs and Tourism. In the case of DWAF, needs are driven primarily by the requirement to implement the new Water Act. The processes to support implementation are currently being formulated, but it is generally accepted that an adaptive approach, incorporating ongoing monitoring and improvement, will be required to achieve the goals of sustainable development.[30–33] DWAF has developed a framework for the implementation of a water resource management strategy (in conjunction with a number of scientists). This framework makes provision for

**Table 1**. List of current and historical biophysical research in the Sabie-Sand catchment.

| Research initiative | Purpose of research (duration in brackets) | Products | Scale at which problem addressed | Source |
|---|---|---|---|---|
| Kruger National Park Rivers Research Programme (KNPRRP) | To contribute to the conservation of rivers through developing an ability to predict the response of rivers to management and disturbance. (1987–1999). | Improved knowledge of dynamics and ecology of river systems. Adaptive management programme for rivers. | Several catchments with a focus on the Sabie-Sand within the KNP. | 6, 10 |
| | | Integrated Catchment Information System (ICIS). Established interdisciplinary network of scientists, managers and landowners. | | 11 |
| River Health Programme (RHP) | To assess and report on the ecological state of river ecosystems. (1996 – ongoing). | Biologically-based indices of river health. Assessment of river health, using these indices. | National but advanced in the Sabie-Sand catchment. | 5, 12, 13 |
| Working for Water Programme | To quantify the extent and impact of invasion by alien plants and the costs and benefits of clearing. (1995–1999). | A management plan for invasive alien plants. Cost–benefit analysis for alien plant clearing. | Sabie-Sand catchment. | 14, 15 |
| Land care initiative | To develop a catchment management strategy for the Sand sub-catchment, with focus on rehabilitation. (1997 – ongoing). | Recommendations covering a comprehensive range of catchment management activities. | Sand sub-catchment. | 16 |
| Hydrological research in small catchments | To quantify the effect of afforestation, deforestation and burning on streamflow and water quality. (1956 – ongoing). | Accurate quantification of water use by commercial plantations and natural vegetation. | Small sub-catchments. | 17, 18 |
| Hydrological process studies | To develop an understanding of the effect of forestry on catchment hydrology. (1984–1997). | An understanding of water use by different tree species and vegetation types. | Individual plants or plant communities. | 19, 20, 21 |
| Land cover | To derive a comprehensive assessment of land cover to underpin management decisions. (1998). | Database of 27 satellite-derived land cover types at a scale of 1:50 000. | National. | 8 |
| Operating rules for Injaka Dam | To be able to predict the effects of extraction levels on instream flow requirements. (1998 – ongoing). | Hydrological systems model to underpin operating rules for the Dam. | Marite River sub-catchment. | 22 |
| Water quality monitoring by forest industry | Compliance with environmental certification of forestry products. (1997 – ongoing). | Regular reports on selected indicators of river health. | Individual plantations. | 23 |
| Alien plant biocontrol | Control of alien plants that impact negatively on streamflow. (1987 – ongoing). | Several agents of biocontrol released. | Extent of alien plant distribution. | 24, 25 |
| Cumulative effects assessment | Development of a framework for integrated catchment management plans. (1999 – ongoing). | Framework for developing an integrated catchment management plan. | Sabie-Sand catchment. | 26 |
| Instream flow requirements study | The integration of instream flow requirements and dam operations to support the provision of the human and environmental reserves. (1995 – ongoing). | Quantification of instream flow requirements using the Building Block Methodology. | Sabie-Sand River system. | 27, 28 |
| Water situation assessment model | To develop a planning tool that would provide information on the balance between water supply and demand on a catchment basis. (1998 – ongoing). | Model based on the quantification of available water resources and demands in a catchment. | Quaternary catchment or any aggregation thereof. | 29 |

continual auditing and reporting around goal achievement towards the desired class (a class refers to the state of a river system relative to a pristine state; there are several classes defined by the degree of modification from the pristine state). This process (Fig. 2) provides a useful framework for the discussion of information needs. Our analysis will focus on the components of the process that relate directly to the management of the biophysical resource (shaded areas in Fig. 2). Note that all the processes required to support this management framework cannot be shown here.

DEAT needs information that will serve the requirements for environmental reporting. This department has recognized the need for improved environmental information to support decision-making and management, a demand that arose from Agenda 21.[34] South Africa is currently building on international models to establish a prototype for national-scale environmental reporting, but regional and catchment-scale reporting are still at an early stage. The essence (and advantages) of DEAT's new approach to reporting lies in its description and analysis of trends in the causes (drivers and pressures) and impacts of environmental problems through reporting, so that solutions can be formulated during the early stages of an environmental concern. This approach provides a framework for continual improvement in management practices and policy revision.

## How well does historical research serve current needs?

The demands for information relevant to catchment management, and the information required to meet them for the Sabie-Sand catchment, are summarized in Table 2. As indicated there, many of these needs can be met by information arising from historical research programmes, but some obvious gaps exist.

There is a large store of information available to meet the demands of water resource management. In particular,

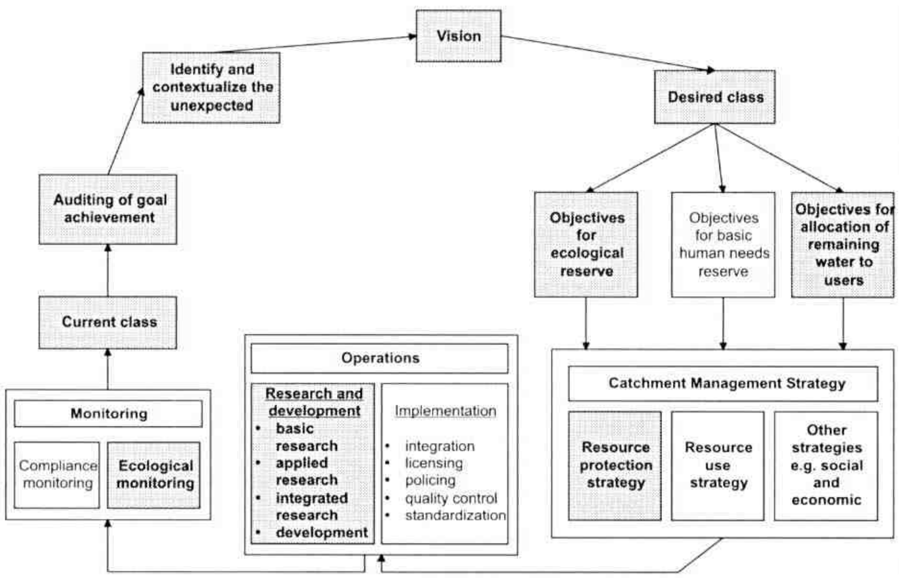


**Fig. 2**. A model process for the ongoing strategic adaptive management of water resources (for protection and allocation aspects) on a catchment basis (adapted from Rogers *et al.*[33]). The shading indicates the components that impact directly on the management of the biophysical resource.

there is information to satisfy the description of the current and desired classes for resource health and to determine the objectives for meeting the ecological reserve. (A class refers to a category of resource health. The desired class is therefore a target category for long-term protection and management. The objectives refer to measurable goals for indicators of ecological integrity such as biota, and variation and volume of water flow.[30] The assumption is that when these objectives are met, the desired class for the resource will be achieved.) The fact that the current and desired classes have not been described for the Sabie River system is due to a gradual phasing-in of reserve determinations to match available capacity for these operations rather than an absence of information. The information requirements relating to ecological monitoring and auditing are also well supported by available knowledge. This store of information and knowledge has resulted primarily from research that has focused on the development of classification systems, databases, and indicators of and measurement techniques for ecosystem health.

Knowledge is deficient in two broad categories: First, knowledge that is directly related to our understanding of the biophysical resource and how it functions; the second is related to people's perceptions and needs associated with the resource and the goods and services it provides.

Within the first group the obvious knowledge gaps relate to the ecological relationships between terrestrial and aquatic systems at the catchment scale, and the ability of these ecosystems to absorb the effects of development. In the Sabie River system, for example, researchers are uncertain as to the degree of sedimentation that can be ascribed to hydrological regime versus human activity.[57] Improved understanding of ecosystem functioning and resilience to impacts will enhance management in several areas. Improved knowledge in this area will allow decision-makers to contribute to a realistic description of the vision for their resource (Fig. 2) and which is set with the recognition of the constraints to the capacity of the resource to support a range of uses and developments. Other areas where research is needed are in the methods and approaches to ecological restoration and the improved understanding of cumulative impacts of human activities on the ecosystem. In addition, reliable, long-term data are needed to provide a baseline against which to monitor change.

Within the second group of knowledge gaps, it is evident that the perceptions, needs and values of the resource-poor (in particular agricultural) sector of the catchment population as well as downstream Mozambique, are poorly understood. Perceptions influence the way in which resource users view the resource and the benefits they derive, or do not derive, from it. Resource management will thus benefit from a better understanding of the social and economic importance of the resource and how these aspects relate to the protection of the biophysical characteristics of the resource. There is also a need for the development of processes and principles that will facilitate equitable and peaceful trade-offs (supported by knowledge of the costs and benefits of potential management decisions) between various water user sectors, in particular in cases where there is competition and potential conflict over the resource.

Table 2 reveals obvious areas of knowledge deficiency, but it also suggests emerging knowledge requirements that are perhaps less easy to describe. One of these is the need to accept, incorporate and prepare for uncertainty in management scenarios (Table 2, 'identify the unexpected'). This relates, to a large extent, to the requirement to understand and predict the nature of the driving forces and pressures (such as changes in land use patterns and people's aspirations) that impact on the resource and how the resource responds to these changes. In order for researchers and resource managers to acknowledge, understand and effectively manage change in the biophysical environment, they must change their thinking. This approach involves a move away from the paradigm of the 'balance of nature' towards acceptance of variability and stochasticity,[58,59] to one that seeks best practices for managing a biophysical environment that is variable in time and space.

Other types of questions important to the management process that are perhaps also not clearly discernible from Table 2, may be questions around the activities performed to arrive at the required biophysical knowledge. In other words, do we know enough about how researchers and managers should operate in order to generate knowledge, given South Africa's need for social transformation and addressing past inequities? Researchers and managers should be asking to what extent their activities promote, for example, cooperative governance and capacity development.

## Suitability of the Sabie-Sand catchment as a case study

### The Sabie-Sand catchment: a premier research destination

The Sabie catchment has received more than its fair share of research attention over the past decade. It is a moot point whether this degree of attention is justified, but the amount of data collection and analysis done here has provided a useful basis from which to develop guidelines for future research and management.

The attention that has been visited on the Sabie came about for a number of rea-

**Table 2**. The requirements for information relevant to catchment management, the degree to which they are met, and gaps in information for the Sabie-Sand catchment. The demand sectors are based on the needs of DWAF (see Fig. 2) and of DEAT (indicated in column 1).

| Demand | Required information | Available information | Gaps in knowledge |
|---|---|---|---|
| Current class | The degree of modification relative to pristine conditions. | Rivers database providing record of pristine condition.[35]<br>Classification system for ecological condition.[36,37]<br>Degree of modification: catchment situation assessments[38,39] and river monitoring results.[40,41] | None, although current class not described for this catchment. |
| Auditing of goal achievement. | Current and desired class information. | | No description of current and desired class (context for monitoring results). |
| (goal = specified class and associated quality objectives) | Monitoring outputs (preferably long-term, measured data for resource quality and quantity). | Resource quality and quantity monitoring results: Weir data (flow and water quality),[42] Instream Flow monitoring results,[28] and River Health Programme monitoring results.[43] | |
| Indentify and contextualize the unexpected | Monitoring outputs over time.<br>Analyses of biophysical trends for scenario-building to predict and prepare for several possible outcomes. | Resource quality and quantity monitoring results: Weir data (flow and water quality),[42] Instream flow monitoring results,[28] and River Health Programme monitoring results.[43] | The full incorporation of change and uncertainty into the biophysical prediction and management system. |
| Vision | Stakeholder needs and expectations.<br>Understanding of system potential and constraints. | Stakeholder needs for organized agriculture, conservation and forestry.[44–46]<br>System variability.[6,47–49] | Stakeholder needs for resource-poor agriculture and downstream international neighbours, and the cultural requirements of indigenous people.<br>Links between terrestrial and aquatic ecosystems poorly understood. Environmental carrying capacities for expanding use sectors not understood. |
| Desired class | Ecological importance and sensitivity.<br>Social and economic importance.<br>Ability of system to respond to restoration efforts. | Ecological importance and sensitivity.[30,50]<br>Expert ecological knowledge.<br>Tacit ecological knowledge.<br>Vulnerable and sensitive zones: Environmental Management Framework, DEAT.[51] | Economic and social importance.<br>Restoration/rehabilitation ecology. |
| Objectives for ecological reserve | Natural benchmarks (pristine condition).<br>Described current and desired class.<br>Ecological importance and sensitivity. | Benchmarks:<br>Rivers database providing a record of pristine condition.[35] instream flows,[28,41,42,52] and hydrological information systems.[11,47]<br>Ecological importance and sensitivity.[30,50] | Described current class. |
| Objectives for allocation of remaining water to users | A quantification of the reserve.<br>Existing use (demand).<br>Projected increase in demand. | Aspects of reserve determined[28] and River Health bio-indicator results.[43]<br>Water use and projected demand by forestry, irrigation & domestic sectors.[16,38,39]<br>Predicted allocatable water.[29] | Formal Reserve determination.<br>Water use by non-forestry crops.<br>Water use and demand by resource-poor agriculture.<br>Dealing with over-allocation when existing use or demand exceeds available supply (methods to determine equitable trade-offs). |
| Resource protection strategy | Database of sensitive areas.<br>Current and desired future states.<br>Analysis of implications for attaining and maintaining desired State. | National wetland inventory,[53] ENPAT (Environmental potential atlas)[51] and EMF (Environmental Management Framework),[51] DEAT.<br>Drivers and Pressures of Current State.[54] | Described current and desired class.<br>Methods of ecological restoration.<br>Predicting costs and benefits of achieving desired state. |
| Research and development | Knowledge of dynamics and interaction between ecosystem components. | KNPRRP publications.[6,10,55] | Links between terrestrial and aquatic ecosystems poorly understood. |
| Ecological monitoring | River health indicators and indices (scoring systems).<br>Monitoring techniques. | River health indicators and indices.[31] IFR study indicators,[28] Institute for Water Quality Studies indicators,[41] Kruger National Park River Research Programme indicators,[32] and Forestry indicators.[23]<br>River Health Programme,40 Institute for Water Quality Studies,[41] Kruger National Park,[55] and Forest Industry monitoring techniques.[23] | None. |

*Continued on p. 354*

**Table 2** *(continued from p. 353)*

| | | | |
|---|---|---|---|
| Identification of drivers, pressures and state for environmental resporting, providing management guidelines and for policy revision.<br><br>(DEAT requirement) | Appropriate, sensitive environmental indicators that show cause and effect.<br><br>Long-term and reliable monitoring data on environmental variables.<br><br>Inventory of state.<br><br>Analysis of development trends and projections of further demands. | Extensive information for forestry, formal agriculture and conservation.[38,39]<br><br>Population growth information (DEAT, South African State of the Environment report).[56]<br><br>Land use information (South African State of the Environment Report),[56] and satellite images.[8] | Resource-poor agriculture.<br><br>Patterns of land use change (in progress).<br><br>Future population demands and expectations.<br><br>Consumption patterns and changes in consumption patterns (e.g. extent of recycling).<br><br>Links between land use and quality and quantity of the resource. |
| Impacts<br><br>(DEAT requirement) | Knowledge of sensitive indicators of environmental impact.<br><br>Monitoring data on environmental impact variables. | South African wetlands inventory (DEAT),[53] Institute for Water Quality Studies instream indicators,[41] River Health,[40] forestry sector[23] and Kruger National Park,[55] monitoring results.<br><br>Remote sensing (land cover change data).[8] Cumulative Impacts Assessments.[26] | Knowledge of cumulative impacts.<br><br>Techniques for predicting cumulative impacts and scenario-building.<br><br>Restoration/rehabilitation ecology.<br><br>Information on impacts of change in socio-economic status of population. |

sons. First, it is a scenically attractive area in which to work. The Mpumalanga escarpment and the Kruger National Park are among South Africa's premier tourist regions, and scientists are happy to work there for the same reasons that tourists pay money to visit the area. Secondly, the catchment had real problems. These included the impacts of large-scale forestry on streamflow in the upper catchment, compounded by the effects of invading alien plants, growing pressure from agriculture and the needs to uplift the standards of rural people in the mid-catchment, significant river management problems in a nationally important conservation and tourist area, and the presence of an international border. The catchment is also small enough to limit the study of problems to manageable proportions, as well as to enable feasible modelling of the outcomes of management actions. The neighbouring Olifants catchment, by comparison, has many of the attractions of the Sabie, but is much larger and has vastly more complex impacts arising from industry and mining in the upper reaches, and cumulative effects of these developments in the lower catchment. The fact that much research attention was focused on the Sabie area also acted as a 'magnet' for more research — the existence of good data made it more feasible for additional research projects to start here rather than in other areas.

### Drawbacks associated with the Sabie-Sand catchment

The large amount of research and data on the Sabie catchment also brings drawbacks. The first issue that arises is the value of the assessment provided in this paper, in terms of a generic model for use in other, less well-researched catchments. For many other South African catchments, fewer data are available. We believe that this 'drawback' should not be viewed as a serious constraint to the provision of guidance to future catchment research. Rather, the abundance of available information allows us to examine the value of the research, and to select the approaches that are most useful for transfer to other catchments. In this way, we believe that research programmes in other catchments can be made more effective.

Another drawback of the focus on this catchment that is often raised, is the issue of comparability and thus the feasibility of transferring lessons from this catchment to others. Many of South Africa's catchments are much larger, and occur in much more arid areas. In addition, many have large impoundments or interbasin transfers by which flow is altered or regulated — the Sabie has not been subjected to such large-scale development and is almost unique in this respect. These criticisms around comparability are indeed valid, but they should not discourage researchers from extracting lessons based on experiences in a selected catchment.

There is no catchment in South Africa that is fully representative of all situations in the country, and the selection of the Sabie-Sand as a case study area was made in recognition of this.

DWAF has, since its inception, been an engineering department that provided engineering solutions to the problems of the time. The fundamentally different new priorities of sustainably managing a vital resource that is severely over-utilized, while at the same time uplifting rural communities by ensuring access to basic water rights, meant that new approaches are required. For the first time, ecologists, limnologists and resource managers have a legally mandated and vital role to play alongside engineers in arriving at new management solutions. The lessons learnt here for the approaches to research and management may therefore be more important than the technical solutions themselves. In this respect, the Sabie catchment provides a rich platform for exploring and designing new approaches to resource management.

Our findings here are preliminary and not conclusive. However, the knowledge gaps shown in Table 2 allow us to make broad recommendations for future research.

## Recommendations for future research

Historical research initiatives in the Sabie-Sand catchment serve current resource management needs relatively well. Activities such as the measurement and monitoring of water resources are well catered for through the River Health Programme, for example, while others (such as information relating to the needs of resource-poor people and the links between land activities and river health) will require greater research focus. For research to provide a more complete set of tools and knowledge to support resource management, researchers must continue to refine the existing knowledge base but they must also undertake to fill the gaps.

Table 2 provides a framework that CMAs and other decision-makers can use to identify areas of knowledge deficiency in their catchment. They may, by recognizing areas where knowledge is lacking, be in a better position to direct research funds. The suggested framework presented here, and identification of knowledge gaps within it, is not exhaustive, but it provides an approach that will stimulate thinking and support decisions around the type of research that will be required to meet knowledge deficiencies.

Capacity building and social transformation provide an important context for natural resource research in South Africa. Given South Africa's history, it is easy to understand why researchers should seek opportunities to redress past inequities and indeed, some funding agencies consider only those research proposals that demonstrate the intention to build capacity in previously disadvantaged groups and individuals. Research that supports the management of water resources offers such opportunities. In particular, our framework highlights that management requires a better understanding of previously marginalized stakeholders' aspirations and needs relevant to the water resource. Successful biophysical management relies on research that recognizes and engages the interface between biophysical and social aspects. Researchers also need to seek opportunities to transfer skills and to incorporate feedback from local communities into their activities, instead of only developing research products. Researchers' and managers' pursuit for knowledge that will support biophysical management therefore needs to be integrated with social research and strategies that will empower people to participate in the resource management process.

Future research should also aim to draw together scientists from terrestrial and freshwater backgrounds to an even greater degree than in the past. It should also attempt to engage managers on a constructive basis. Here, the concept of 'gaps in knowledge' extends to 'gaps in networks'. These network gaps are barriers to a holistic and integrated approach to ecosystem management, and they should be addressed in research programmes. Furthermore, this analysis shows that the interactions between biophysical, social and economic aspects of the resource require greater understanding if researchers and managers are to understand their collective impact on behaviour related to water resources. Fortunately, with a new mandate to achieve cooperative governance at all levels of government and civil society, there will be better opportunities to make cross-boundary interactions explicit in research.

Restoration ecology (the process of assisting the recovery and management of ecological integrity) is a young science but is becoming increasingly important as a management component as water and other natural resources degrade in the face of unsustainable development. In the Sabie-Sand catchment, restoration is already an issue with the large-scale removal of alien plants and efforts to improve the quality of the land in the former homeland area of the catchment.[16] The resource management system proposed by the Water Act also makes provision for active restoration in cases where it is jointly agreed by stakeholders that the desired condition for a river is an improvement from the current condition. Ecological restoration is usually an expensive and long-term process, and with limited funding, resource managers will need to weigh up restoration costs of various approaches with the potential for successful rehabilitation.

The lack of knowledge about water consumption by certain forms of land use is a further important gap. Research has resulted in a great deal being known about water use by plantation forestry for example[17–21,60], while the effects of other forms of crop agriculture on streamflow reduction is not known. As a result, forestry has been singled out in South Africa's new water law as a 'streamflow reduction activity', which has economic consequences for the industry in the form of streamflow reduction charges. The large amount of attention paid to the hydrological impacts of forestry is a source of some irritation to the forest industry. Clearly, research needs to focus on the effects of other important forms of land use on water resources, and to place these impacts within the wider context of efficiency, sustainability and socioeconomic value addition associated with resource use.

Furthermore, the matter of affordability should be mentioned. Research requires funding and it is only in cases where research can clearly be shown to improve water resource management, and therefore result in progress towards economic growth and sustainable development, that it will attract funding. The case for research funding, in turn, must be justified on the basis of sound resource economics. This is another example of the need for new approaches which go beyond single-discipline studies.

Finally, we can pose questions around the value of the collection of research (some starting as far back as 1956) that has been carried out in this catchment. Has it made a real impact and if so, by whom have the benefits been felt? Would it have made any difference to anyone, had this research not been conducted?

The role of research is to generate knowledge and to disseminate this learning in order to create a better-informed society. The research projects and programmes discussed here have done this at different levels and to differing extents. Some have been more focused on basic research, while others have invested more in knowledge generation and application, and communicating research results. For example, a number of the research initiatives in Table 1 have played a significant role in influencing policy and, in particular, contributed to the development of the National Water Act. Others have involved long-term experiments that have promoted a better understanding of basic biophysical functioning, such as how certain plants use water. Each type of research has a role to play. However, the mix of catchment-based research will require a stronger research vision and a conceptual framework that will guide better-coordinated research activities. These features will promote more relevant, more integrated research outputs, and outcomes that could be measured in terms of real impacts on society attitudes and activities and, ultimately, on resource quality.

A conceptual framework to guide water resources research should also be flexible to reflect changing societal and management needs. The world in which researchers and managers operate is subject to continuous change, and is made more complex by an escalating rate of change. Part of the challenge of research is therefore to meet objectives within this ever-changing environment, to ensure that research will be continuously receptive and responsive to deliver relevant products that can meet current and future needs for knowledge. This is achievable, but we (researchers and research managers) must re-examine our current approaches to research delivery and put effort into combining change management with research management activities. Research programmes should learn from hindsight and experience. However, research must also be more proactive and strategic in dealing with current needs in a coordinated fashion and in anticipating future requirements. When we consider our collective activities in 50 years' time, we should be able to show, with confidence, that resources have been invested wisely in research, and that the returns on this investment are visible and measurable in the changes it intended to promote.

We thank the Water Research Commission for funding this work, and Anna Ballance, Charles Breen and Kevin Rogers for constructive contributions to the development of these ideas.

1. Ashton P., Braune E., Maaren H., McKenzie R.S., Orpen W.R.G., Pitman W., Rooseboom A., Schultze R.E., van Rooyen P.G. and van Vuuren S.J. (1999). Hydrological science in South Africa: 1995–1998. *S. Afr. J. Sci.* **95**, 250–268.
2. Davies B.R. and J. Day (1998). *Vanishing Waters*. University of Cape Town Press, Cape Town.

3. Turton A.R. (1999). Water demand management: a case study from South Africa. *School of Oriental and African Studies, Occasional Paper, London.* Online: http://www.soas.ac.uk/Geography/WaterIssues/
4. Karr J.R. (1999). Defining and measuring river health. *Freshwat. Biol.* **41**(2), 221–234
5. Hohls D.R. (1996). *National Biomonitoring Programme for Riverine Ecosystems: Framework Document for the Programme.* RHP Report Series no. 1, Institute for Water Quality Studies, Pretoria. Online: http://www.csir.co.za/rhp/reports/
6. Breen C.M., Quinn N.W. and Deacon A. (1994). *A Description of the Kruger National Park Rivers Research Programme (Second Phase).* Foundation for Research Development, Pretoria.
7. Chunnet, Fourie and Partners (1987). The Sabie River water resource development study: briefing paper for assessing the in-stream water requirements of the natural environment and to assess the impact of the water resources development. Chunnet, Fourie and Partners, Pretoria.
8. Thompson M. (1996). A standard land-cover classification scheme for remote-sensing applications in South Africa. *S. Afr. J. Sci.* **92**, 34 –42
9. Central Statistical Service (1991). *Population Census.* Government Printer, Pretoria.
10. Breen, C.M., Quinn, N.W. and Mander J. (1997). *A Description of the Kruger National Park Rivers Research Programme (Third Phase).* Foundation for Research Development, Pretoria
11. Integrated Catchment Information System. Online: http://www.ccwr.ac.za/icis/
12. Roux D.J. (1998). The National River Health Programme as a tool in effective water resource management. In *Proceedings of the Annual Conference of the South African Affiliate of the International Association of Impact Assessment – Innovative Tools and Methods for Meeting the Challenge of IEM in South Africa.* 30 September – 2 October 1998, Cathedral Peak Hotel, Drakensberg, pp. 231–237. International Association for Impact Assessment South Africa.
13. Murray K. (1999). *National Aquatic Ecosystem Biomonitoring Programme: National Implementation Assessment.* NAEBP Report Series no. 8, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria.
14. Nel J., Bailey C. and Van Wilgen B. (1999). *Management Plan for Alien Vegetation in the Sabie-Sand Catchment.* CSIR report ENV-S-C 99097, CSIR, Pretoria.
15. Le Maitre D.C., van Wilgen B.W., Gelderblom C.M., Bailey C., Chapman R.A., and Nel J.A. (in press). Invasive alien trees and water resources in South Africa: case studies of the costs and benefits of management. *Forest Ecology and Management.*
16. Pollard S.R., de Mendiguren P.J.C., Joubert A., Shackleton C.M., Walker P., Poulter T. and White M. (1998). *Save the Sand. Phase 1: Feasibility Study. The Development of a Proposal for a Catchment Plan for the Sand River Catchment.* Department of Water Affairs and Forestry, Pretoria.
17. Nanni U.W. (1971). The Mokobulaan research catchments. *S. Afr. For. J.* **78**, 5–13.
18. Scott D.F. and Lesch W. (1997). Streamflow responses to afforestation with *Eucalyptus grandis* and *Pinus patula* and to felling in the Mokobulaan experimental catchments, South Africa. *J. Hydrol.* **199**, 360–377.
19. Dye P.J., Poulter A.G. and Hudson K. (1995). A comparison of the water use of common riparian forests and grassland. Report FOR-DEA 925, CSIR, Pretoria.
20. Dye P.J. (1996). Climate, forest and streamflow relationships in South African afforested catchments. *Commonwlth For. Rev.* **75**, 31–38.
21. Dye P.J., Poulter A.G., Soko S. and Maphanga D. (1997). *The Determination of the Relationship between Transpiration Rate and Declining Available Water for* Eucalyptus grandis. Water Research Commission Report no. 441/1/97, Pretoria.
22. Sellick C. (1998). Sabie River catchment: system model and operating rules: inception report. Charles Sellick and Associates, Pretoria.
23. Weir F. and Diedericks G. (1998). *Water Quality Monitoring 1997 Report.* SAFCOL Environmental Section, Mpumalanga. SAFCOL, Sabie.
24. Olckers T. and M.P. Hill (eds) (1999). Biological control of weeds in South Africa (1990–1998). African Entomology Memoir no. 1, Entomological Society of Southern Africa, Pretoria.
25. Van Wilgen B.W., van der Heyden F., Zimmermann H.G., Magadlela D. and Willems T. (2000). Big returns from small organisms: developing a strategy for the biological control of invasive alien plants in South Africa. *S. Afr. J. Sci.* **96**, 148–152.
26. Van der Heyden F., Mitchell I. and Megown R. (1999). *Integrating Cumulative Effects Assessment with Catchment Management Planning.* CSIR Report ENV-S-I-9922, Pretoria.
27. Tharme R.E and King J.M. (1998). *Development of the Building Block Methodology for Instream Flow Requirements and Supporting Research on the effects of Different Magnitude Flows on Riverine Ecosystems.* Water Research Commission Report no. 576/1/98, Pretoria.
28. Tharme R. (1997). *Instream Flow Requirements of the Sabie-Sand River System.* Final report of the IFR workshop, 18–22 August 1996. Department of Water Affairs and Forestry, Pretoria.
29. Watson M.D., De Jager F.G.B., McKenzie R.S. and Schultz C.B. (1999). Water balance model: overview and latest developments. Paper presented at the *Ninth South African Hydrology Symposium:* 29–39 November 1999, University of the Western Cape, Bellville.
30. Department of Water Affairs and Forestry (1999). *Resource Directed Measures for Protection of Water Resources. Volume 2: Integrated Manual, Version 1.0.* Pretoria. Online: http://www-dwaf.pwv.gov.za/iwqs/waterlaw/rdm
31. Roux D.J., Kleynhans C.J., Thirion C., Hill L., Engelbrecht J.S., Deacon A.R. and Kemper N.P. (1999). Adaptive assessment and management of riverine ecosystems: the Crocodile/Elands River case study. *Water SA* **25**(4), 501–512.
32. Rogers K.H. and Biggs H. (1999). Integrating indicators, endpoints and value systems in strategic management of the rivers of the Kruger National Park. *Freshwat. Biol.* **41**, 439–451.
33. Rogers K.H., Roux D.J. and Biggs H. (2000). Challenges for catchment management agencies: lessons from bureaucracies, business and resource management. *Water SA* **26**(4), 505–511.
34. Department of Environmental Affairs and Tourism (1996). *State of the Environment Series: Environmental Indicators,* comp. R.D. Walmsley and J.R. Pretorius. DEAT, Pretoria.
35. Fowler J., Dallas H. and Janssens P. (2000). *Rivers Database: A User Manual.* NAEBP Report Series no. 11, Department of Water Affairs and Forestry, Pretoria.
36. Kleynhans C.J. (1996). A qualitative procedure for the assessment of the habitat integrity status of the Levuvhu River (Limpopo system, South Africa). *J. aquat. Ecosyst. Hlth* **5**, 1–14.
37. Kleynhans C.J. and Hill, L. (1999). Appendix R1: preliminary ecoregion classification system for South Africa. In *Resource Directed Measures for Protection of Water Resources, vol. 3: River ecosystems* (Version 1.0), pp. R11–R118. Online: http://www-dwaf.pwv.gov.za/iwqs/waterlaw/rdm
38. Department of Water Affairs and Forestry (1990). *Water Resources Planning of the Sabie River Catchment. Study of Development Potential and Management of Water Resources* (10 volumes), prep. E.C.H. Sellick and B.W. Bonthuys. Pretoria.
39. Department of Water Affairs and Forestry (1991). Joint Inkomati Basin Study Performed for the Tripartite Permanent Technical Committee of the Kingdom of Swaziland, the Republic of Mozambique and the Republic of South Africa. Prepared by Jibsconsults. Pretoria.
40. River Health Programme. Online: http://www.csir.co.za/rhp/
41. Institute for Water Quality Studies. Online: http://www-dwaf.pwv.gov.za/directorates/iwqs/
42. O'Keefe J.H., Weeks D.C., Fourie A. and Davies B.R. (1996). *A pre-impoundment study of the Sabie-Sand River system, Mpumalanga with special reference to predicted impacts on the Kruger National Park. Vol. 3: The Effects of Proposed Impoundments and Management Recommendations.* Water Research Commission Report no. 294/3/96, Pretoria.
43. Thirion C., Todd C. and Moolman J. (2000). Assessment of the state of the Crocodile, Sabie and Olifants rivers based on the SASS Invertebrate Index. Draft report to the Water Research Commission, Pretoria.
44. Department of Water Affairs and Forestry (2000). Proposal for the establishment of a catchment management agency for the Inkomati Basin. Prepared on behalf on the Inkomati CMA Reference Group, by MBB Consulting Engineers, ACER (Africa), Environmental Management Consultants, and AWARD, under the auspices of the Mpumalanga Regional Office of the DWAF. Pretoria.
45. Rogers K.H. and Bestbier R. (1997). *Development of a Protocol for the Definition of the Desired State of Riverine Systems in South Africa.* Department of Environmental Affairs and Tourism, Pretoria.
46. Woodhouse P. and Hassan R. (1999). *Catchment Management Agencies: Interests, Access and Efficiency. Inkomati Basin Pilot Study.* Department of Water Affairs and Forestry, Pretoria.
47. Anon. (1990). Kruger National Park Rivers Research Programme. *Water for Nature. Hydrology: Sabie River Catchment.* Department of Water Affairs, Pretoria.
48. Birkhead A.L., Heritage G.L., James C.S., Rogers K.H. and van Niekerk A.W. (2000). *Geomorphological Change Models for the Sabie River in the Kruger National Park.* Water Research Commission report no. 782/1/00, Pretoria.
49. Carter A.J. and Rogers K.H. (1989). Phragmites reedbeds in the Kruger National Park: the complexity of change in riverbed state. In Conference *Proceedings: 4th South African National Hydrological Symposium,* 20–22 November, Pretoria.
50. Kleynhans C.J., Bruwer C.A., Kilian V., Weston B., van Wyk N. and Sellick C. (1998). *A Procedure for the Determination of the Ecological Reserve for the Purpose of the Planning Estimate.* Institute for Water Quality Studies, Pretoria.
51. Department of Environmental Affairs and Tourism, Pretoria. Online: http://environment.gov.za/docs/2000/enpat/index.html/
52. Van Coller A.L. and Rogers K.H. (1996). *A Basis for Determining the Instream Flow Requirements of the riparian Vegetation along the Sabie River within the Kruger National Park.* Centre for Water in the Environment Report no. 2/96, University of the Witwatersrand, Johannesburg.
53. Department of Environmental Affairs and Tourism, Pretoria. Online: http://environment.gov.za/soer/nsoer/
54. Van Wyk E., Breen C.M., Jaganyi J.J., Ndala S., Rogers K.H., Roux D., van Wilgen B.W. and Venter F. (1999). Environmental pressures, status and responses in the Sabie-Sand catchment with special reference to river management. Draft report to the Water Research Commission, Pretoria.
55. Kruger National Park Rivers Research Programme publications. Online: http://www.ccwr.ac.za/knprrp/
56. Department of Environmental Affairs and Tourism. South African State of the Environment Report. Online: http://www.ngo.grida.no/soesa/
57. Heritage G.L., van Niekerk A.W., Moon B.P., Broadhurst L.J., Rogers K.H. and James C. (1997). *The Geomorphological Response to Changing Flow regimes of the Sabie and Letaba River Systems.* Water Research Commission Report no. 376/1/97. Pretoria.
58. Pickett S.T.A., Parker V.T. and Fiedler P.L. (1992). The new paradigm in ecology: implications for conservation biology above the species level. In *Conservation Biology: The Theory and Practice of Nature Conservation, Preservation and Management,* eds P.L. Fiedler and S.K. Jain. Chapman and Hall, New York.
59. Rogers K.H. (1997). Operationalising ecology under a new paradigm. In *Enhancing the Ecological Basis of Conservation: Heterogeneity, Ecosystem Function and Biodiversity,* eds S.T.A. Pickett , R.S. Ostfeld, M Shachak and G.E. Likens, pp. 60–77. Chapman and Hall, New York.
60. de Wit M., Crooks D. and van Wilgen B.W. (in press). Conflicts of interest in environmental management: estimating the costs and benefits of a tree invasion. *Biological Invasions.*