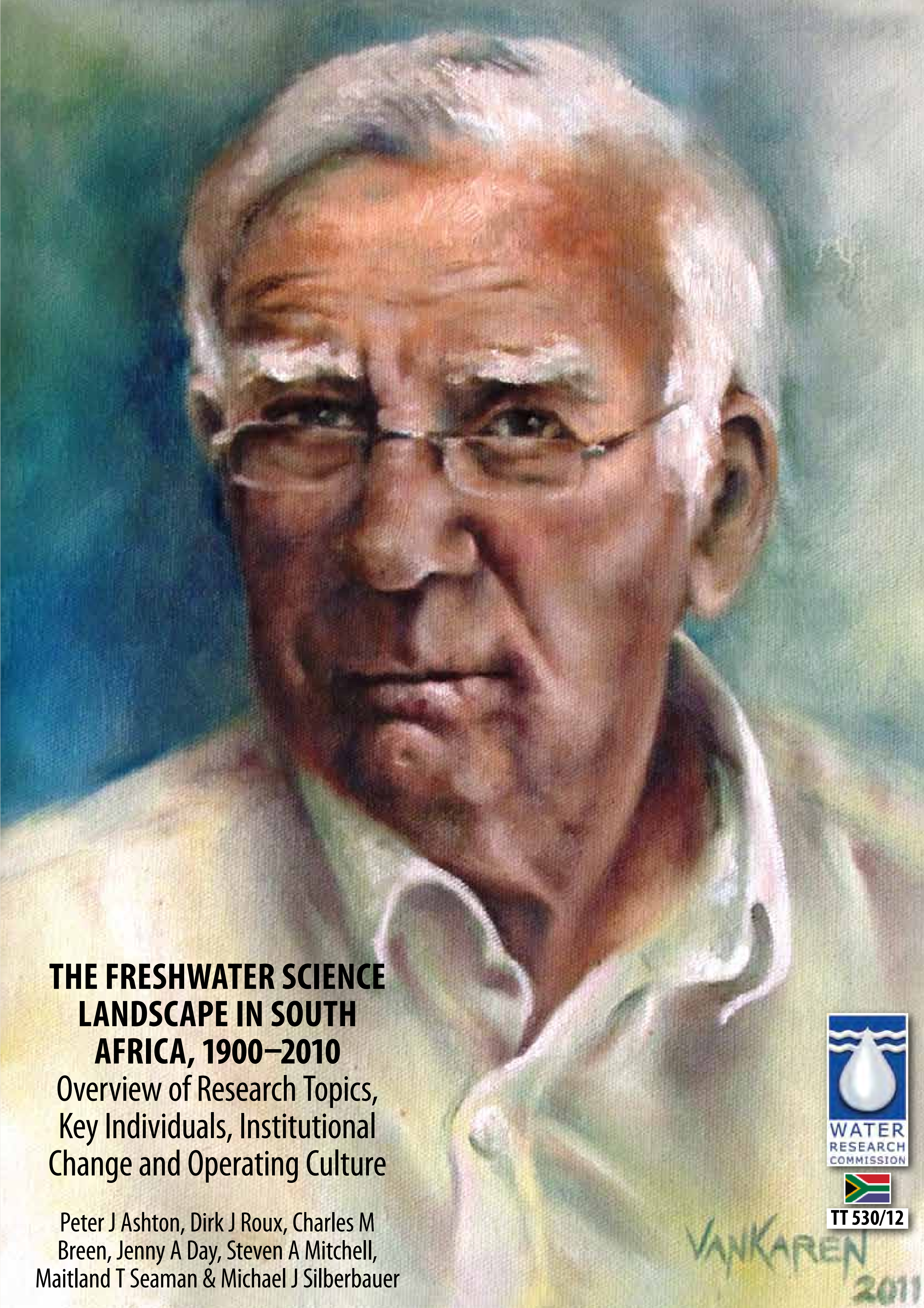

THE FRESHWATER SCIENCE LANDSCAPE IN SOUTH AFRICA, 1900–2010

Overview of Research Topics, Key Individuals, Institutional Change and Operating Culture

Peter J Ashton, Dirk J Roux, Charles M Breen, Jenny A Day, Steven A Mitchell, Maitland T Seaman & Michael J Silberbauer

WATER RESEARCH COMMISSION
TT 530/12

THE FRESHWATER SCIENCE LANDSCAPE IN SOUTH AFRICA, 1900-2010

OVERVIEW OF RESEARCH TOPICS, KEY INDIVIDUALS, INSTITUTIONAL CHANGE AND OPERATING CULTURE

Report to the

Water Research Commission,

Compiled by

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The compilers of this report dedicate the reports to Professor Brian Allanson as a mark of our sincere recognition for the exceptional contribution he has made over several decades, to aquatic sciences in South Africa and to the careers of so many South African aquatic scientists

The frontispiece is a copy of a portrait of Emeritus Professor Brian Robert Allanson that was painted by Karen van der Merwe from a photograph taken at his Knysna Laboratory in 2010.

ACKNOWLEDGEMENTS

The authors and compilers of this report thank their institutions for agreeing to their attendance at the planning meetings that were held during the early stages of preparing this document (**Appendix A**). These institutions include the University of the Free State, North-West University, the Department of Water Affairs, the University of Johannesburg, the Water Research Commission, the National Research Foundation, the University of Limpopo, the Nelson Mandela Metropolitan University, Rhodes University, The South African Institute for Aquatic Biodiversity, the South African Environmental Observation Network, the University of KwaZulu-Natal, the University of Cape Town, Cape Nature, KZN Wildlife, the Limpopo Department of Economic Development, Environment and Tourism, Aurecon and the CSIR.

We are grateful to the regional co-ordinators (listed in **Appendix A**) for successfully organizing the five regional meetings where the compilation team met with local aquatic scientists. These meetings yielded a wealth of information for this report.

In compiling this report, we acknowledge with thanks those individuals who contributed text, stories, diagrams, photographs and reference materials. We sincerely hope that this report has dealt with these materials sensitively and in a balanced way. The individuals who contributed materials are listed on the front cover as 'Contributors'. Others read through sections of text relevant to their efforts and provided feedback to the team – their contributions are acknowledged with sincere thanks.

We are also grateful to the auxiliary staff, all those librarians, secretaries, technicians, data typists and hired hands whose dedicated and often unrecognized toil has contributed so much to the advancement of aquatic science in South Africa.

Particular thanks are due to the following individuals:

- Professor C.G. Palmer, previously of the National Research Foundation (NRF), now Director of the Unilever Centre for Environmental Water Quality at Rhodes University, for facilitating the formal release by the NRF of the confidential report on the state of limnology in South Africa, produced by Professor Bill Williams in 1989, for this study.

- Dr Chris Dickens of the Institute for Natural resources, University of KwaZulu-Natal in Pietermaritzburg, for facilitating contact with Emeritus Professor Brian Moss at the Institute for Sustainable Water, Integrated Management and Ecosystem Research at the University of Liverpool, for permission to use his 1999 report on the state of eutrophication research in South Africa for this study.

- Tony Dold of the Selmar Schonland Herbarium at Rhodes University for providing published material and photographs of Mary Agard Pocock.

- Ms Desiree Lamoral, The Information Centre Manager at the Institute for Commercial Forestry Research, at the Pietermaritzburg campus of the University of KwaZulu-Natal for kindly providing a copy of the article by Balarin, Brink and Glen on the botanical collections made by Mary Agard Pocock.

We thank the Water Research Commission for providing funds to start this study.

In a project of this magnitude it is almost inevitable that we have inadvertently overlooked or omitted or failed to acknowledge the contributions that were made by a few individuals or organizations. We apologize unreservedly if this has happened.

EXECUTIVE SUMMARY

Objectives of this study

This study originated as a consultancy contract issued by the Water research Commission.

The effective management of South Africa's water resources requires an informed and reliable scientific foundation to provide appropriate evidence-based information to guide decision-making. Aquatic sciences, together with engineering, provide this foundation and help to ensure that the country's water resources are managed sustainably.

This study set out to record the evolution of aquatic sciences in South Africa since 1900, identify the external driving forces that helped to direct research, pinpoint the individuals and institutions responsible for shaping the ways in which aquatic sciences developed, and determine the extent to which aquatic sciences have contributed to effective management of South Africa's water resources.

This study focussed on inland surface waters, while recognizing the clear and inextricable links between surface waters and atmospheric water, groundwater, estuaries and open oceans – the other parts of a single, indivisible hydrological cycle.

Approach followed

This study started with the compilation of a list of names of aquatic scientists, which was subsequently expanded by inputs received from the first few rounds of e-mail exchanges with colleagues locally and abroad.

This was followed by five meetings in regional centres (Pietermaritzburg, Pretoria, Bloemfontein, Grahamstown and Cape Town) where members of the project team met with aquatic scientists who were able to participate in these meetings. These meetings provided opportunities for individuals to share stories of their experiences – especially in relation to their main research themes, key individuals who had influenced their careers and specific events or situations that affected them.

Everyone on the mailing list was encouraged to contribute written material and the project team sorted through the contributions and collectively arranged these into a chronological order. In some instances, there were obvious gaps in the sequence of events and specific individuals were asked to contribute sections on, for example, their particular institutions. Finally, the report has been through a total of nineteen revisions where the compilers read through the document and contributed new materials of suggested ways to improve and strengthen the document. The final document represents the collective efforts of a large number of committed aquatic scientists who share a common passion for their work.

Primary conclusions

All aquatic scientists share a common aspiration that our lives and careers should be interesting, fulfilling and rewarding. We all aspire to the feeling that our careers contribute to the well-being of society and that our efforts are not in vain. Unfortunately, the current reality reveals that there are too few career opportunities available for the number of aquatic scientists who are interested in research, while there is a simultaneous, diminished capacity within water resource management institutions to take up and apply research findings.

The situation we face in South Africa is mirrored elsewhere in the world. Robert Wetzel's eloquent preface to the third edition of his textbook on limnology (Wetzel, 2003) places the root cause of this situation on those efforts to provide society and decision-makers with rapid answers, without ensuring that these answers are supported by a solid scientific foundation. This, in turn, is linked inextricably to the general failure of societies to properly educate students at all levels and the general public. As Wetzel notes, it is essential for everyone to recognize, and accept, that "*intellectual creativity is essential to excellence in science and that excellence in science is essential if we are to ensure the most effective and cost-effective management of our resources*".

The fact that the problems we face in South Africa are the same as those faced elsewhere in the world is not an excuse for complacency or a false sense of comfort. It is our responsibility to deal with, and solve, the problems we face as a result of escalating demands for water that are not matched by the supplies that are available, and fact that the integrity of these supplies continues to be compromised by widespread pollution plus the impending threats posed by global climate changes. Put simply, if we do not, collectively, provide cost-effective and sustainable solutions to the water quantity and water quality problems in our country then we will experience escalating problems of social unrest.

The poor spatial and temporal distribution of our water supplies, plus our absolute dependence on water storage reservoirs to supply water during the dry months of the year, means that we should deploy the best skills available in engineering and aquatic sciences to develop the long-term solutions that are needed. Unfortunately, it appears that the urgency of these issues is not widely recognized and we do not see sufficiently decisive efforts directed to strengthening the national cadre of aquatic sciences and engineering. In particular, efforts that are directed towards solving pressing problems linked to water supply and water pollution appear to be proceeding at a snail's pace, or, most unfortunately, are simply linked to 'quick-fix' solutions that are seldom underpinned by firm scientific evidence. Inevitably, these types of solutions are seldom sustainable.

An unfortunate feature that was revealed during our study is the progressive decline in the extent and integrity of national monitoring systems. There is clear evidence that, from a water quality perspective, for example, fewer sites are being monitored, fewer variables are being analyzed and the frequency of sample collection is declining. Given the progressive and widespread decline in water quality across South Africa, the reduction of monitoring efforts will hamper management of the country's water resources. On the principle that 'if a resource is not measured then it cannot be managed', there is a clear and urgent need to expand and improve our monitoring efforts and not to reduce them.

Our study revealed the clear importance of at least some degree of institutional stability, where people stay in the system long enough to develop a sense of shared responsibility and proud ownership of outcomes. Importantly, institutional or organisational memory is based on explicit information in reports and data systems as well as the tacit knowledge that resides in people and their inter-relationships. Those tacit and explicit elements have shaped, and will continue to shape, aquatic science in South Africa. If we simply 'eject' experienced aquatic scientists and engineers from our institutions, for whatever reason, we lose an enormous 'bank' of knowledge and insight that could still be usefully deployed.

There is clearly a need for an improved, broader, national vision to guide the development, deployment and funding of aquatic science in South Africa, so that aquatic scientists can continue to contribute to the sustainable management of the country's water resource base.

A large number of aquatic scientists were trained in South Africa during the last four decades and, despite the attrition caused by emigration and retirement, more of these individuals are available than was the case in earlier years. However, the number of aquatic scientists that conduct active research in South Africa continues to decline and the post-1990 period has not delivered sufficient new talent to meet the needs of a country where "*Limnology, as the science which, with hydrology, underpins effective water resource management, should be amongst the most carefully nurtured of all South African scientific enterprises*" (Williams, 1989). This is partly a reflection of a global decline in the field of limnology (Wetzel, 2003) and, more importantly, a consequence of the failure of the South African education system at all levels to educate and enthuse a new generation of scientists and engineers (Cherry, 2010).

Despite the availability of larger numbers of people working in the various fields of aquatic sciences, many of these individuals only have a broad, generalist training in environmental sciences. This generalist training seldom equips them properly to deal with the complex, trans-disciplinary problems that they face in their careers. The shortage of career opportunities in research fields has forced many individuals to choose employment opportunities as consultants. For a variety of reasons, this impedes open interactions and communication between individuals working for different firms, and those who move more frequently between firms experience far less continuity of work in terms of building a career; this is accompanied by a decrease in the collective institutional memory.

The majority of active aquatic scientists that we approached during this study expressed their keenness to participate in the project. However, few could find the time to do so because of pressing administrative commitments and responsibilities. This begged the question: in such a crowded work-life, how much space is left for reflection, creativity and originality?

Our clear impression is that the original strong focus on excellence in science is waning. The passion for scientific excellence as the only criterion that mattered for the outstanding individuals of the past now seems to have been eroded by the pressing need to accomplish more 'things' in less time.

Many of the younger generation of scientists indicate that the typical job description of an aquatic scientist is unclear and has changed dramatically from what it used to be prior to 1980. It seems that the boundary between scientific researchers and consultants has become almost completely blurred.

There is a clear and unequivocal need for greater numbers of strong, decisive scientific leaders in aquatic sciences. By leaders, we mean individuals who have extensive experience in one or more fields of aquatic science, who have established an international reputation for their work, who have a passion for accuracy, precision and attention to detail, and to whom 'excellence' is the hallmark of everything that they undertake. Strong leaders are able to bring together teams of like-minded individuals whose passion for their work drives them to succeed, and who are driven by their desire to excel. Here, it is important to distinguish between 'leaders' and 'managers', whose main function is to oversee and guide the administrative aspects of research programmes, to 'create the space' that is needed by good leaders and their teams. Far too often, it seems that some institutions regard a 'good manager' to be capable of 'good leadership'; in reality, this happy state of affairs is seldom true. Unfortunately, when the leadership and management roles are combined and the individual concerned lacks the appropriate blend of expertise and experience plus adequate support, they seldom fulfil their potential.

The important function that SASAqS used to fulfil in bringing together water resource managers and aquatic scientists from all disciplines needs to be revitalized. This would help to re-establish, extend and strengthen the previously strong links between aquatic scientists and those individuals in Government who are responsible for water resource management and policy. In turn, this would enable aquatic scientists to more clearly understand the specific information needs of water resource managers and also to help them to transfer research findings to water research managers.

Recommendations

Based on our findings in this study and the conclusions that we have drawn, we make the following recommendations.

There is a clear and urgent need to strengthen the South African education system at all levels so that it provides an environment within which the individuals that have the ability and drive to develop a career in science and / or engineering can flourish. Equally problematic is the need to create sufficient opportunities for aquatic scientists and engineers to develop meaningful careers and work together to achieve the goals articulated in our national vision for water resources. A key part of the career development of all individuals is the crucial role played by experienced mentors who can guide less experienced colleagues to develop their careers. At the same time, the education system needs to develop technically-skilled individuals who are capable of developing, adapting, manufacturing and maintaining the instrumentation and software that are pivotal to the scientific enterprise.

Equally importantly, aquatic scientists must appreciate the need to deploy their skills and experience to address those societal needs that relate to their fields of expertise. It is no longer possible for an aquatic scientist simply to undertake research on a subject or issue that has little or no relevance to broader society. This will require aquatic scientists to realize that they have a responsibility to provide ‘solutions’ that will help to solve a particular problem experienced by society.

The national systems of water quantity and water quality monitoring urgently need to be expanded and improved to the point where they can provide reliable data to aquatic scientists and engineers. These data form the foundation upon which defensible decisions can be made on the sustainable management of our water resources.

The rivers and the water they transfer connect our people and economies with their neighbours across local and international boundaries and South Africa cannot isolate itself from the rest of the region. Because of our economy, experience and competencies, we also have a broader responsibility to develop the regional understanding and competencies that are required to make the inevitable trade-offs in ways that are equitable and sustainable. Ideally, the WRC should continue to be pivotal in developing and sustaining the partnerships that are needed to enable aquatic sciences research to take a regional, social-ecological systems perspective of the management of water resources.

As we increasingly appreciate the need to understand socio-ecological systems at landscape, continental and global levels, and as our awareness grows of the need to acknowledge and engage complexity, it is clear that we need to adopt a more programmatic approach to research. As the scale of investigation increases to landscape-level studies focussed on complex social-ecological systems, the issues of concern are too broad and too complex to be addressed by a single project. To deal with such issues requires the integration and synthesis of insights and findings from a number of research projects covering multiple disciplines. Ideally, these projects should form a logical set of components within a research programme. Importantly, a programme is not simply a collection of related projects, but is driven by a shared aspiration to strive for a common goal.

Effective research programmes seek to produce new knowledge, new alliances and new understanding that influence the longer term management and governance of the use of a particular resource. Effective research programmes require us to build knowledge systems that span disciplinary, research, policy, and operational domains; this takes much more time and requires more persistence and investment in social capital than is typically afforded by individual research projects.

One way to build, maintain and strengthen synergy between research teams is to have a clear, over-arching funding system that guides and co-ordinates research efforts and addresses clear national priorities. The current approach to research funding tends to focus on single projects or small groups of projects, and only provides a partial solution to the problem. The approach used so successfully by the Co-operative Scientific Programmes (CSP) to fund and guide research programmes during the 1980s could serve as a useful starting point for re-evaluating funding systems.

TABLE OF CONTENTS

LIST OF FIGURES AND ILLUSTRATIONS

LIST OF ACRONYMS USED

AWARD	Association for Water and Rural Development
BBM	Building-Block Methodology
CAPE	Cape Action Plan for the Environment (later changed to 'Cape Action for People and the Environment')
CAR	Centre for Aquatic Research, University of Johannesburg
CAT	Centre for Aquatic Toxicology, Rhodes University
CCWR	Computing Centre for Water Research
CDNEC	Cape Department of Nature and Environmental Conservation
CEO	Chief Executive Officer
CERM	Consortium for Estuarine Research and Management
CMA	Catchment Management Agency
CSIR	Council for Scientific and Industrial Research, South Africa
CSIRO	Commonwealth Scientific and Industrial Research Organization, Australia
CSP	Co-operative Scientific Programmes
CWE	Committee for Inland Water Ecosystems (see IWE)
DEA	Department of Environmental Affairs, South Africa
DEAT	Department of Environmental Affairs and Tourism, South Africa
DRIFT	Downstream Response to Imposed Flow Transformations
DSIR	Department of Scientific and Industrial Research (UK)
DWA	Department of Water Affairs, South Africa
DWAF	Department of Water Affairs and Forestry, South Africa
ECRU	Estuarine and Coastal Research Unit
EDCs	Endocrine-disrupting compounds
EIA	Environmental Impact Assessment
FOSAF	Federation of South African Flyfishers
FRD	Foundation for Research Development
FRU	Freshwater Research Unit, University of Cape Town
FSR	Flow Stressor Response
GAP	Group on Aquatic Productivity
GIS	Geographical Information System
GLOW	Great Lakes of the World (GLOW)
HRI	Hydrological Research Institute (later IWQS, now RQS, *q.v.*)
IBP	International Biological Programme (1964-1974)
IBP-PF	International Biological Programme, Productivity of Freshwater section
IBT	Inter-basin transfer (of water)
ICMA	Integrated Coastal Management Act (Act No. 24 of 2008)
ICSU	International Council for Scientific Unions
IES	Institute for Environmental Sciences, University of the Free State
HOD	Head of Department
IFS	Institute for Freshwater Studies, Rhodes University
IWE	Inland Water Ecosystems Programme
IWQS	Institute for Water Quality Studies, Dept of Water Affairs
KNP	Kruger National Park
KNPRRP	Kruger National Park Rivers Research Programme
KZN	KwaZulu-Natal
KZNPCD	KwaZulu-Natal Planning and Development Commission (was NTRPC – *q.v.*)
KZNWL	KwaZulu-Natal Wildlife
LSSA	Limnological Society of Southern Africa (now SASAqS – *q.v.*)
Mm^3	Million cubic metres (of water)
NAEBP	National Aquatic Ecosystem Biomonitoring Programme
NALMS	North American lake Management Society
NEAP	Nutrient Enrichment Assessment Protocol

NEMA	National Environmental Management Act (Act No. 107 of 1998)
NGO	Non-Governmental Organization
NIWR	National Institute for Water Research, CSIR (*q.v.*)
NPES	National Programme in Environmental Sciences, CSIR (*q.v.*)
NRF	National Research Foundation
NRIO	National Research Institute for Oceanology, CSIR
NSBA	National Spatial Biodiversity Assessment
NTRPC	Natal Town and Regional Planning Commission (now KZNPDC – (*q.v.*)
NWA	National Water Act (Act No. 36 of 1998)
PAAP	Provisional Algal Assay Procedure
PPC	Pretoria Portland Cement Company
RAU	Rand Afrikaans University (now University of Johannesburg)
RDM	Reserve determination methods
RHP	River Health Programme
RQO	Resource Quality Objective
RQS	Directorate: Resource Quality Services, Department of Water Affairs, South Africa, (formerly known as HRI and IWQS, *q.v.*)
RWQO	Receiving Water Quality Objective
RU	Rhodes University
S_2A_3	South African Association for the Advancement of Science
SADC	South African Development Community
SAIAB	South African Institute for Aquatic Biodiversity
SAEON	South African Environmental Observation Network
SAM	South African Museum
SAM	Strategic Adaptive Management
SANBI	South African National Biodiversity Institute
SANParks	National Parks, South Africa
SASAqS	Southern African Society of Aquatic Scientists (previously LSSA – *q.v.*)
SASS	South African Scoring System: a bioassessment tool using invertebrates
SAWIC	South African Water Information Centre
SCOPE	Scientific Committee on Problems of the Environment
SIL	Societas Internationalis Limnologiae: International Society of Limnology (formerly International Association of Theoretical and Applied Limnology)
SPATSIM	Spatial And Time Series Information Modelling System
SRI	Shared Rivers Initiative
TMF	Table Mountain Fund
TPA	Transvaal Provincial Administration
TWQR	Target Water Quality Range
UCT	University of Cape Town
UFS	University of the Free State (previously UOFS – *q.v.*)
UJ	University of Johannesburg (previously Rand Afrikaans University – *q.v.*)
UKZN	University of KwaZulu-Natal
UN-FAO-CIFA	Central Institute of Freshwater Aquaculture, Food and Agricultural Organization, United Nations
UNESCO	United Nations Educational, Scientific and Cultural Organization
UOFS	University of the Orange Free State (now UFS – *q.v.*)
UPE	University of Port Elizabeth
Wits	University of the Witwatersrand
WMA	Water Management Area
WRC	Water Research Commission, South Africa
WSA	Water Services Act (Act No. 108 of 1997)
WWI	First World War
WWII	Second World War
YWG	Yellowfish Working Group

1 INTRODUCTION

1.1 Preamble

Aquatic sciences have morphed dramatically over time from their original, purely biophysical focus. From their roots in the discipline of limnology – the ecology of inland waters – we now have more integration across the whole of the hydrological cycle, including links with groundwater as well as estuarine and near-shore marine systems. While recognizing and accepting that the scope of aquatic sciences has broadened enormously over the years, the core focus of this study deals with the inland waters of South Africa and seeks to record the external driving forces and resulting changes that have taken place in research institutions and their technical achievements since the beginning of the twentieth century. Prior to 1900, the primary focus of aquatic science was directed to taxonomic work as investigators sought to identify and classify the variety of new organisms they encountered. The period from 1900 to the present day covers the time when South African aquatic science – 'limnology' in its broadest sense – developed from the early 'collect them, count them and name them' stages to its present form where the hydrological and biophysical characteristics of inland waters have to be integrated with the social, economic and political issues related to the uses that are made of the country's scarce water resources.

External forces (some of a global nature, such as the two World Wars, the Spanish Influenza epidemic and the Great Depression, and, later, the call for greater accountability and financial self-sufficiency amongst research and academic institutions), accompanied by enormous internal policy, legal and institutional changes in recent years, have dramatically changed the face of aquatic science in South Africa. The sequence of key events and external driving forces is shown in **Figure 1**.

At national scale one of the 'external driving forces' that had profound implications for aquatic science was the pressure for recreational fishing that led to the very strong emphasis given by conservation agencies to the propagation and stocking of rivers and dams with alien fish species. Later this was to find expression in research directed at conserving biodiversity.

Within the discipline of aquatic science, one internal driving force stands out. In 1948, the South African statesman Jan Christiaan Smuts observed: "*Something holistic is at the heart of things and in the nature of this universe, which is not a mere chance or random assemblement of items. The detailed things derive most of their meaning, significance and functioning from the whole of which they are but parts. They are not mere parts but really members of wholes*" (Smuts, 1952). The emergence of holism and the concept of dynamic ecosystems that evolved in the 1940s drove aquatic research into an era, which persists to this day, of understanding the dynamic relationships between the composition, structure, functioning and resilience of aquatic ecosystems. Considerable research was directed at trophic dynamics to explain how energy and material transfers ordered ecosystem composition, structure and function. This approach led to the development of ecosystem modelling, to systems theory and in recent times, to complexity and complex systems ecology. This evolution is clearly evident in the chronology of South African aquatic science.

Notwithstanding a relatively small pool of specialists and relatively limited financial resources, South Africa has a proud history of research in aquatic sciences that can be traced back to the start of the twentieth century, prior to the seminal work of G.E. Hutchinson and his co-workers in the early 1930s (Hutchinson *et al*., 1932). However, almost all of this early work was carried out by taxonomists and other experts based in overseas institutions. In recent years, it has become increasingly clear that the central importance of South Africa's freshwater ecosystems and the need to ensure that they can continue to provide us with adequate quality and quantity of water and the associated ecosystem services requires a firm and reliable research foundation.

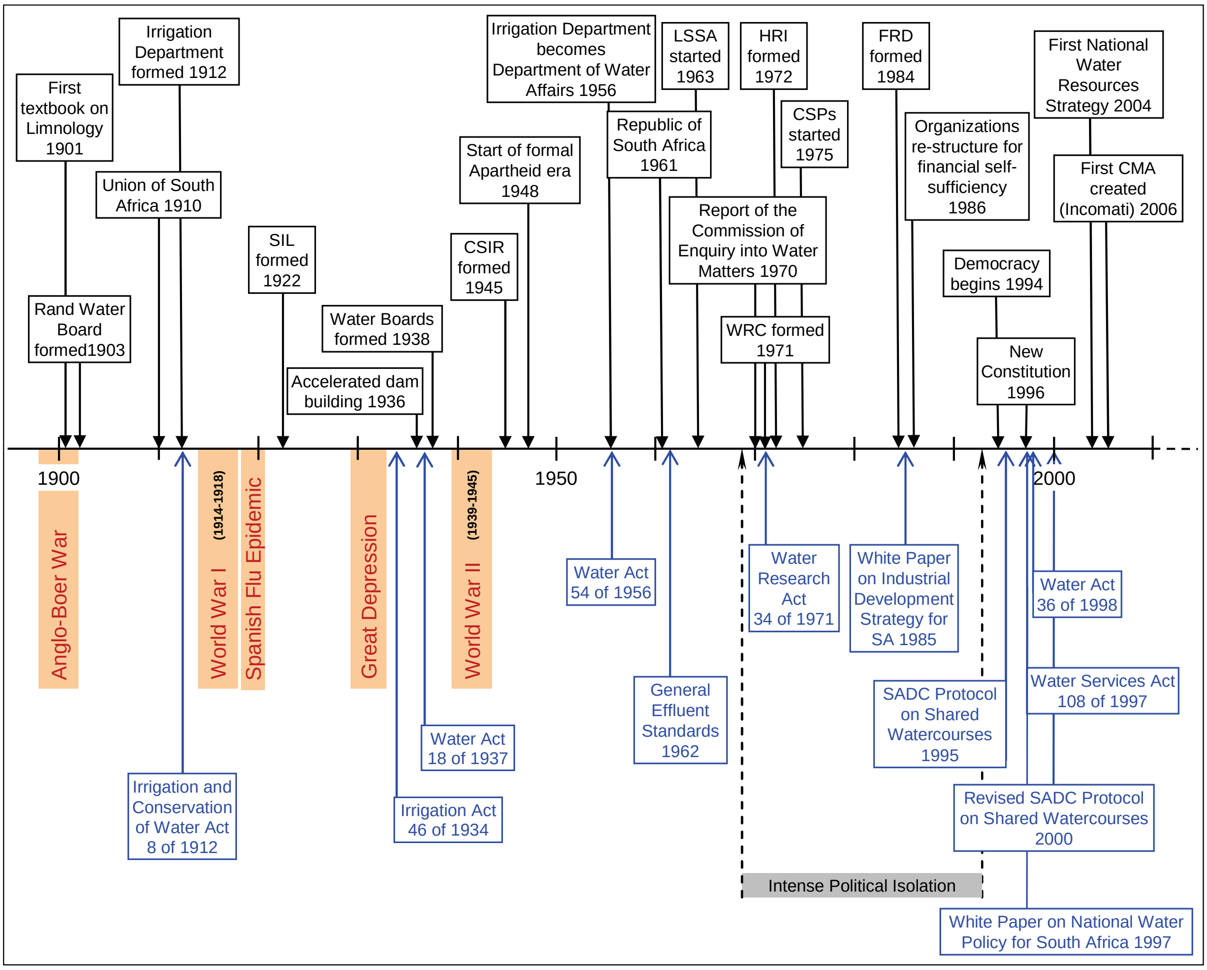


Figure 1. Aquatic science landscape time-line showing the major events and external driving forces that have shaped South African aquatic science since 1900. (**Note**: the abbreviations used in the diagram are explained in the glossary to this report).

Some suggest that the overall South African aquatic science enterprise seems to be lacking vision, losing capacity, internal cohesion and external connectedness, including effective links with management and policy domains (*e.g.* Williams, 1989). In recent years, research efforts appear to be more fragmented, reactive (focussing on short-term contract applications as opposed to longer-term fundamental and strategic research), and driven almost entirely by short-term goals. A most worrying issue is the threatening loss of memory within the aquatic science sector as many of the more experienced practitioners leave the country, retire from employment or pass away. Science is a highly systematic process of knowledge production and depends critically on the memory of past information, methods, investigations and contributors to build the next generation of knowledge. In short, institutional memory is crucial for the development and advancement of all branches of science. So-called “intellectual deforestation” (Landon, 2005) – the strategy of consciously eliminating previous research findings – is a highly counter-productive intellectual enterprise that can have grave consequences for the development of knowledge in any society. This is particularly counter-productive in ecosystem-based disciplines, where rapidly growing external forces have resulted in accelerating changes and where previous research findings often provide the only hint we have as to the pre-industrial nature of such systems. Through this study we hope to provide a chronological perspective that would allow an informed assessment to be made as to whether or not these perceptions are indeed true.

Institutional memory can be defined as "*the means to retain (sic) and transmit information from past to future members*" (Stein, 1995), or "*the ability to encode, store, and retrieve the lessons of history despite the turnover of personnel and the passage of time*" (Levitt and March, 1988). These definitions highlight the need for at least some degree of institutional stability (maintaining memory through people staying in the system long enough to develop a sense of shared responsibility and ownership of outcomes). The definitions also recognise that organisational memory is based not only on explicit information, but also on the tacit knowledge that resides in people, including their inter-relationships. In this study we seek to draw out and integrate those tacit and explicit elements that have shaped, and continue to shape, aquatic science in South Africa.

1.2 Scope and objectives of this study

The effective management of South Africa's scarce water resources requires an informed and reliable scientific foundation to provide appropriate, evidence-based information to guide decision-making. This project reflects on the development of aquatic science in South Africa since 1900 and its likely future trajectory. Although South Africa can be described as having an 'immature national system of innovation', comparative advantage indicators for the country show consistent specialisation (relatively high performance) in aquatic sciences for the period 1981-2001, together with disciplines such as geology and mining engineering, veterinary medicine and animal health, and animal sciences (Albuquerque, 2003).

Recognizing the crucial importance of institutional memory to the development of all scientific endeavours, the specific objectives of this study are to:

- Capture the chronology (sequence of events) that shaped aquatic science in South Africa, including the prominent characters, contributors, findings and decisions, while identifying the evolution of general culture within the discipline and the interactions between aquatic scientists with water resource management; and
- Reflect on the current state and likely future trajectory of aquatic science in South Africa and how the role of aquatic science can be strengthened to meet current and future challenges.

Related review initiatives can be found for groundwater in South Africa (Vegter, 2001), the international development of limnology (mostly work from the northern hemisphere between 1650 and 2000; Kalff, 2002), and more technical overviews of limnological developments in South and southern Africa (Allanson, 2003; 2004). It is important to note that our emphasis is not so much on memory in terms of technical content (as in Allanson, 2004), but rather on memory in terms of the characters; external driving forces (*e.g.* political and economic change); institutions (societies, organisations, academic schools); pivotal projects, discoveries, products and impacts; main areas of common focus; the prevailing culture of science and research (including issues of accountability, funding, dependency, typical activities); and the main teaching influences during different phases of the development of aquatic science in South Africa.

Importantly, this investigation focuses on freshwater and its scope spans all of the major aquatic ecosystems, including rivers, lakes, impoundments and wetlands (and touches on estuaries and groundwater); aquatic taxa, including phytoplankton and benthic algae, aquatic macrophytes, zooplankton and zoobenthos, aquatic invertebrates, fishes and other aquatic vertebrates; aquatic habitats and their composition and structure, including sediments and water chemistry; physical, biological and catchment processes; policy formulation and policy implementation, and the development and application of management techniques.

Perhaps equally importantly, this study is not intended to provide a comprehensive listing of all the technical publications that have been written by South African aquatic scientists. The publications that are referred to in the text represent what that the compilers of this document consider to reflect specific achievements and objectives. Some individuals misinterpreted the objectives of this study and provided the team of compilers with comprehensive lists of their publications. Those publications that were not cited in this report have been listed in **Appendix D** to ensure that they are recorded and are not lost.

1.3 Approach followed

This study was commissioned in the form of a consultancy by the Water Research Commission. As with so many research projects, the original terms of reference for the study reflected a great deal more enthusiasm for the topic than an accurate understanding of the magnitude of the task to be undertaken. Nevertheless, the project was designed and carried out around a number of main steps.

First, a contact list of people with relatively 'long memories' was developed, starting with names familiar to the two commissioned members (Ashton and Roux) and adding to the list based on feedback obtained from initial contacts. With the assistance of regional champions, five regional meetings were held in Pietermaritzburg, Pretoria, Bloemfontein, Grahamstown and Cape Town, respectively. Invitations to attend these meetings were distributed by email and the regional champions were helpful in soliciting key individuals to attend these meetings. A record of the regional meetings with their respective attendees is provided as **Appendix A**, while the names and contact details of everyone who was contacted are provided in **Appendix B**. At each of the regional meetings, several individuals suggested that it would be vital to interview Professor Brian Allanson and obtain his insights into the long-term trends in South African aquatic science. Accordingly, Peter Ashton and Dirk Roux arranged a special meeting with Brian Allanson in Knysna.

During the regional meetings people were encouraged to share stories of their experiences in aquatic science, especially related to main research themes and key individuals that had an influence on their work. Data from these discussions were captured and used to shape a report structure. Subsequent to the final meeting, an incomplete draft report was compiled and circulated to all those on the contact list, including many colleagues who had worked in South Africa but now live overseas. These recipients were asked to make written contributions to the report. All received contributions were incorporated and a second draft report was circulated for a further round of comment. In addition, specific people were approached and requested to make particular contributions related to their fields of interest. Those who provided written contributions are acknowledged as contributors to this report.

During the final stage of collating all the collected and contributed data into a coherent story, five co-compilers (Charles Breen, Jenny Day, Steve Mitchell, Maitland Seaman and Michael Silberbauer) were drawn in to provide a better representation of regional and disciplinary experience on the writing team.

We found that almost all of the people we consulted are deeply and truly passionate about their work in various fields of aquatic science and saw this project as an opportunity to share their experiences and contribute to the future of aquatic sciences in South Africa. At the same time, many people (especially those in senior positions) have little or no 'buffer time' and found that they were unable to participate or contribute as actively they would have wished to the knowledge sharing process provided by this project. As a result, some disciplines, organisations and individual contributions are under-represented in this report.

1.4 Structure of this document

We have divided this report into four sections, to reflect periods of time that we believe are characterized by different stages in the development of South African aquatic science. We refer to these time periods as:

- The early years (1900-1945)
- The middle years (1946-1979)
- The turbulent transitional years (1980-1994)
- The latter years – adapting to change (1995-2010)

Within each section, we have arranged the materials into three sections: 1) chronology of key events; 2) individuals and topics of note; and 3) institutional landscape. This is followed by a section that attempts to draw out discernible trends over time. Finally, the report contains conclusions and recommendations, and a list of some important references that were cited in this document. It is important to remember that this report is not intended to provide a comprehensive listing of all the publications that South African aquatic scientists have produced.

1.5 Exceptional individuals of the past

Many of the pioneers and characters who helped to build the knowledge base of South African aquatic science are no longer with us. However, we remember their contributions through the rich legacy that they have left in the scientific literature and the stories about them that still live on in members of the aquatic community. In this section we briefly highlight the involvement of seven such individuals in the story of aquatic science in South Africa.

1.5.1 Mary Agard Pocock

Mary Pocock (31 December 1886 – 10 July 1977) was an unusually talented person, gaining recognition for scientific research, art and an essay on Brasses. She was to combine her talent for art and scientific exploration to great effect as her career in botany matured. As a young lady in 1899 she was sent to be educated at Bedford High School for Girls in England, returning in 1913 with a BSc degree. After teaching for four years at Wynberg (Cape) Girls High School she returned to England to study with FC Steward at Cambridge. In 1923 she was back in South Africa as a temporary lecturer at the University of the Witwatersrand and over the next twenty years she held similar positions at Rhodes University, the University of Cape Town and the Huguenot University in Wellington.

Mary Pocock's enquiring mind and adventurous spirit led her, in 1925, to join the ethnologist Dorothea Bleek for a six month journey on foot from Livingstone in Northern Rhodesia (now Zambia) through the Barotse floodplains of the upper Zambezi, and then through Angola to

Luanda (Balarin *et al.*, 1999; Dold, 2001). Pocock is best known for her pioneering research on the Volvocales. She started her journey of discovery in 1928 providing new insights into distribution, growth, development and reproduction. Her ‘outstanding work on algae’ was recognised in 1957 when she received the Crisp Medal and Award given by the Linnaean Society of London and later in 1967, when Rhodes University conferred on her a DSc *Honoris causa*. Pocock was one of the characters of botanical exploration in South Africa. She is affectionately remembered by her students and colleagues and especially those who experienced her forays in search of new species of freshwater and marine algae.

1.5.2 Keppel Harcourt Barnard

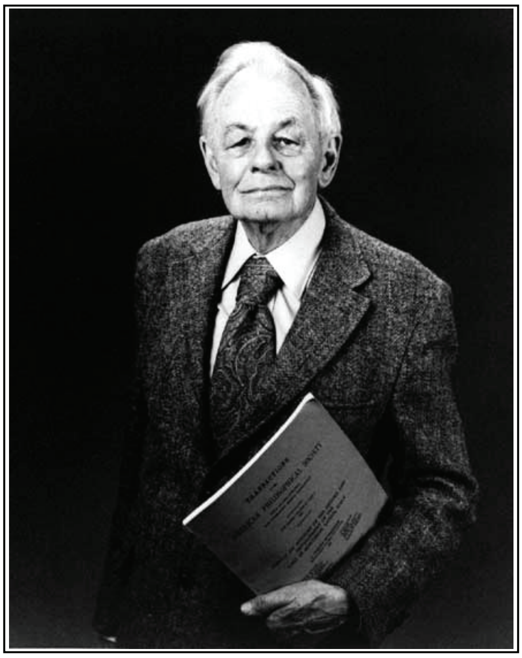
Keppel Barnard (13 March 1887 – 22 September 1964) was born and schooled in London, obtaining a Tripos in Botany, Geology and Zoology from Cambridge University in 1908 and a law degree from the Middle Temple, London, in 1911. He did not practise as a lawyer, however, working instead for a few months as an Honorary Naturalist at the Marine Biological Research Laboratory in Plymouth, before coming out to South Africa and joining the South African Museum (SAM) in Cape Town. Starting as an Assistant when he arrived in 1911, he was employed by the Museum until his retirement in 1956, having been Director since 1946.

After retiring he continued his association with the SAM, studying marine molluscs until his death some eight years later; he was associated with the Museum for 53 years! Barnard was a taxonomic ‘polymath’, having published papers on the taxonomy of freshwater branchiopods, isopods, amphipods, decapods, mayflies, trichopterans and various other insect groups, and fish (Barnard, 1947), as well as marine molluscs, fishes and crustaceans, particularly amphipods, isopods and decapods.

Keppel Barnard produced more than 200 publications, including several books and monographs, during his lifetime. Barnard was no stay-in-the-lab scientist, though. He mounted several collecting expeditions to remote places, including the coast of Portuguese East Africa (now Mozambique) and the Kunene River in northern Namibia, some of them by ox wagon. As a keen mountaineer, he explored many of the mountains of the south-western Cape, where he obtained much of the freshwater material that he described. Barnard was one of the last of a breed of biologists who had both the breadth and the depth of knowledge to make him conversant with almost all animal taxa. It is ironical that the four different species of *Galaxias – a* genus of small fishes from south-western Cape streams – that Barnard described were later ‘lumped’ into one species. Recent genetic studies show, however, that he was correct: there are at least four and probably quite a few more than four, species of *Galaxias*.

1.5.3 George Evelyn Hutchinson

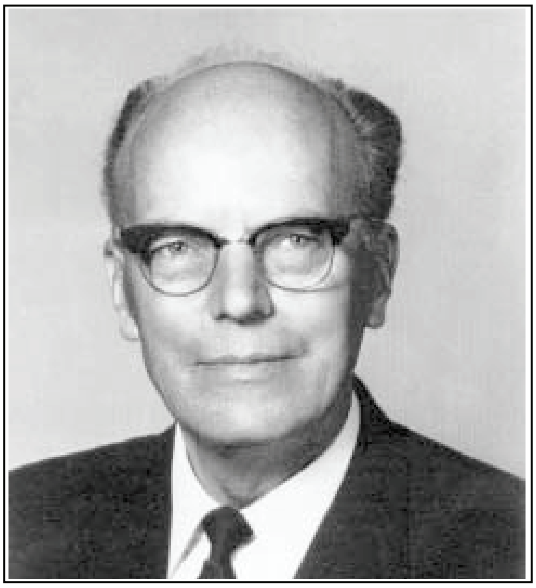
G. Evelyn Hutchinson (30 January 1903 – 17 May 1991) was born and educated in England. In 1925 he was hired on a 3-year contract as a temporary lecturer at the University of the



Witwatersrand. After a year of teaching he worked on pans in the eastern portion of the Highveld and elsewhere, publishing the first significant paper on South African limnology in 1932 (Hutchinson *et al.*, 1932). He also worked on aquatic hemipterans and published several papers on African species, including what is still the seminal paper on South African corixids, notonectids and pleids (Hutchinson, 1929). After leaving South Africa, Hutchinson joined Yale University as a postdoctoral fellow and taught there for the next 43 years. Later he produced a four-volume set of books entitled "*A Treatise on Limnology*" (Hutchinson, 1957; 1967; 1975; 1993), the fourth volume appearing posthumously. He is widely regarded as one of the founding fathers of aquatic ecology and had an enormous influence on limnology and ecology in general.

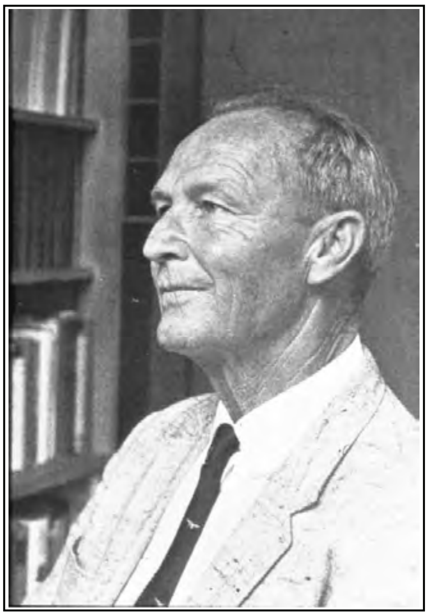
A recent review of Hutchinson's career and his scientific achievements in limnology and ecology over his lifetime (Carruthers, 2011) highlighted the variety of Hutchinson's enormous contributions to freshwater science. Ultimately, his move from South Africa to North America was a tragic loss to the fledgling freshwater science community in South Africa. A 1991 obituary written by Yvette Edmondson, a close colleague of Hutchinson, also emphasized the contribution that Hutchinson's many publications had made to limnology students world-wide (Edmondson, 1991). Sadly, we can only speculate as to what might have been achieved had Hutchinson been able to stay and continue his work in South Africa.

1.5.4 Eduard Meine van Zinderen Bakker



E. M. van Zinderen Bakker (15 April 1907 – 19 March 2002) was born in Friesland in the Netherlands. After graduating with a PhD in Botany at the University of Amsterdam, he taught biology at a school in Apeldoorn until in 1947, when at the age of 40 he emigrated with his wife and two sons to South Africa and joined the Department of Botany at the University of the Orange Free State. With research interests in Quaternary climates, palynology, and the ecology of Africa, he initiated limnological research on the Orange River system and, in 1965, on the Sub-Antarctic Islands of Marion and Prince Edward. This research included palynology, glacial geology, volcanology, limnology, mineral cycling and bioenergetics. In 1966 he established the journal *Palaeoecology of Africa*, which he edited for 20 years. Some months before he died he expressed his philosophy as follows: "The most valuable legacy we can leave to our fellow humans, young and old, is the overwhelming awareness that we are surrounded by countless wonders that do not ask for pseudo-explanations, but can only be answered in the manner that befits the marvels of nature, namely with reverence and with a huge question-mark" (Coetzee, 2001).

1.5.5 John Hemsworth Osborne Day



John Day (25 August 1909 – 24 April 1989) was born near London in England but was brought up in Mozambique (then Portuguese East Africa) and later in South Africa. He completed a first degree in Zoology and Chemistry through Rhodes University, and later a PhD degree through Liverpool University – at the time the only university where it was possible to study oceanography. In the mid-1930s John was employed at the University of Cape Town (UCT), first as research assistant to the intertidal ecologist Prof Alan Stephenson, and later as a lecturer. Almost single-handed, John Day surveyed the invertebrate fauna of the rocky shores of southern Africa from Lüderitz to northern KwaZulu-Natal. When World War II broke out in 1939, John returned to the UK and joined the Royal Air Force. As well as seeing action (during which he was injured, losing a leg), he was involved in the development of radar and its predecessors. Returning to UCT after the war, he developed the first estuarine research programme in southern Africa.

John Day was an inspiring, if daunting, teacher and a stalwart defender of academic freedom and of the scientific enterprise. He believed that good fundamental data are essential for understanding the functioning of aquatic ecosystems and his surveys of the rocky shores, inshore waters and estuaries of South Africa are still models of good practice equalled in very few other parts of the world. He always emphasized the importance of quantitative analyses and early on he recognized with delight the potential value of computers in analysing complex ecological data.

1.5.6 Katherine Marjorie Frances Scott

Marjorie Scott (19 January 1913 – 26 April 1998) was awarded a BSc degree from the University of Cape Town in 1933, an MSc with Distinction in 1934 and a PhD in 1939. After living for some years in Argentina, she returned to South Africa at the beginning of World War II, to the Department of Zoology at UCT, during which time her research switched to estuaries. She later moved to the National Institute of Water Research of the CSIR, where she worked until her retirement at the end of 1978. The move to the CSIR resulted in her turning to freshwater biology, influenced by her active involvement in Arthur Harrison's survey of the Great Berg River. Marjorie found herself increasingly drawn into taxonomic studies, firstly of adult chironomids and later of both larval and adult trichopterans (caddis flies), which gradually became her main research interest. In 1963 Marjorie was transferred to Grahamstown in the Eastern Cape, where she directed a Research Unit of the CSIR's National Institute for Water Research, and later to the Albany Museum to take charge of what became the National Collection of Freshwater Invertebrates, of which she was curator until she retired. It must also be noted that Marjorie was a brilliant scientific illustrator and she has left a legacy of drawings that are scientifically accurate and aesthetically pleasing.

Retirement" gave Marjorie the opportunity to devote more of her time to the study of Trichoptera, All this work was done on a voluntary basis as an Honorary Research Associate of the Albany Museum. In addition to the solid scientific value of her written papers, Marjorie's fascination with her work never faltered and she worked steadily, five days a week, at the Albany Museum, right up until a few months before her death at the age of 85.

1.5.7 Arthur Desmond Harrison

Arthur Harrison (24 December 1921 – 30 December 2007) was born in Kalk Bay near Cape Town. His father was AC Harrison, who edited Piscator, the journal of the Cape Piscatorial Society, for many years. Arthur received his BSc, MSc and PhD degrees from the University of Cape Town, his PhD being a study on the aquatic ecology of the Great Berg River (from which he contracted typhoid fever during his studies). This work, published in the *Transactions of the Royal Society of South Africa,* (Harrison, 1958a, 1958b) was the earliest on South African rivers and represented some of the earliest significant publications on the ecology of rivers anywhere.

From the outset Arthur balanced limnological and applied studies – one of his earliest papers concerned the effects of acidic mine pollution on the streams of the South African Highveld. After his PhD, Arthur joined the National Institute of Water Research of the CSIR, later taking up a Rockefeller Grant for bilharzia research at the University of Rhodesia in Salisbury. Following the Rhodesian Unilateral Declaration of Independence (from the UK), Rockefeller funding was withdrawn under sanctions against Rhodesia, and Arthur returned to South Africa, briefly becoming Professor of Zoology at the University of Natal in Pietermaritzburg before accepting a professorship in Biology at the University of Waterloo in Canada. During his tenure in Canada he spent time on St Vincent Island in the West Indies, and in Addis Ababa in Ethiopia. He finally 'retired' to Cape Town.

During all these years he had a particular interest in chironomids (non-biting midges), publishing many papers, especially on the African fauna. There was hardly a subject that Arthur could not discuss intelligently with the experts, and when computers came along he took to them like a duck to water in his private capacity and in connection with his scientific work, which went on long after his retirement. Arthur was an immensely knowledgeable, insightful and productive scientist and a charming person. He was a limnological pioneer in Africa when the field was in its infancy. His breadth of knowledge of freshwater invertebrates was unrivalled, and his biogeographic insights (*e.g.* Harrison and Agnew, 1962; Harrison,

1978) have stood the test of time. Further, he showed that good biological research can be produced even under most arduous circumstances.

2 THE EARLY YEARS (1900-1945)

2.1 Chronology of key events

1901 – Publication of the first textbook on limnology, *Handbuch der Seenkunde: Allgemeine Limnologie*, by F.A. Forel, Professor of Physiology at the University of Lausanne in Switzerland. The book represents the results of his research of more than 30 years on Lake Geneva (Kalff, 2002).

1908 – The first journal for limnology is established, namely *Internationale Revue der gesamten Hydrobiologie und Hydrographie*, encompassing limnology and hydrology (Kalff, 2002).

1910 – Consolidation of the colonial and republic governments in South Africa into a single entity, the Union of South Africa.

1912 – The African National Congress comes into being, in response to the poor and indirect representation of Black South Africans in the Union Government.

1912 – The Department of Irrigation is created within the Ministry of Lands and the first Director was Francis E. Kanthack, who had many years of experience in irrigation in the Punjab, India and had been Director of Irrigation in the Cape since 1906 (Beinart, 2004).

1912 – Promulgation of the Irrigation and Conservation of Water Act (Act No. 8 of 1912), which emphasizes the government's view that perhaps the most important use of water was for irrigation of agricultural crops, followed by the supply of water to towns and emerging industries. This marked the start of construction of numerous large water storage reservoirs (*e.g.* Hartbeespoort, Darlington, Van Rynevelds Pass) that were destined to provide water primarily for irrigation uses.

1914 to 1918 – World War I

1915 – The first comprehensive ichthyological survey of a South African estuary is conducted on the Zwartkops estuary in response to the concerns expressed by recreational fishermen that commercial netting is causing reductions in fish numbers (Whitfield, 1998).

1916 – Britain establishes a Department of Scientific and Industrial Research (DSIR).

1918-1920 – the Spanish flu epidemic kills an estimated 50 million people worldwide; this is equivalent to about 3% of the world's population (which then stood at 1.6 billion). At least 250 000 people die in South Africa, making it one of the five worst-hit countries in the world (Phillips, 1990).

1922 – Establishment of the *International Association for Theoretical and Applied Limnology* (SIL) with 401 founding members and representation from nearly all continents (Kalff, 2002).

1923 – First water quality samples collected from Zeekoevlei (Cape Town) by J. Muller, with a site map made and photographs taken of the occasion. At this time Zeekoevlei is only accessible after a three-mile walk from Muizenberg along the beach!

1925 – G. Evelyn Hutchinson joins the University of the Witwatersrand; three years later he leaves South Africa for Yale University in the USA.

1929 – A decade of economic boom is ended by "Black Tuesday" (October 29, 1929). The Wall Street Crash leads to the Great Depression.

1930 –The term ecosystem is coined by Roy Clapham to mean the combined physical and biological components of an environment. British ecologist Arthur Tansley later refined the term, describing it as: "*The whole system, including not only the organism-complex, but also the whole complex of physical factors forming what we call the environment*" (Tansley, 1939).

1932 – Johanna Schuurman publishes an important first paper on the micro-fauna and micro-flora of Florida Lake on the Witwatersrand (Schuurman, 1932). She also works with G. Evelyn Hutchinson on the pans of the Eastern Transvaal (Hutchinson *et al.*, 1932).

1936 – Joseph Omer-Cooper is appointed as a Senior Lecturer in the Zoology Department of Rhodes University and in 1937 he became Head of Department. With a tertiary education from Cambridge University and the University of Durham, Omer-Cooper was responsible for the development of Entomology at Rhodes University. He worked mostly on the taxonomy of dytiscid beetles.

1939 – Germany invades Poland; Britain and France declare war on Germany two days later, marking the start of World War II.

1942 – Raymond Lindeman's seminal paper titled '*The trophic-dynamic aspect of ecology*' is published in the journal Ecology (Lindeman, 1942). Raymond Laurel Lindeman (1915-1942) was an ecologist whose graduate research is often credited with forming the foundations of the field of ecosystem ecology. Lindeman experienced considerable resistance from reviewers and editors who did not want to publish his paper and it was only after the intervention of Odum that his paper was accepted for publication!

1945 – The end of World War II. The Allies form the United Nations in an effort to foster international cooperation and maintain peace. The Soviet Union and the United States emerge as rival superpowers, setting the stage for the Cold War, which lasts for the next forty-four years. The fall of the Berlin Wall in 1989 marked the 'official' end to the Cold War.

1945 – The CSIR was formally established on 5 October 1945 as a "body corporate" outside of the South African Public Service.

2.2 Individuals and topics of note

The establishment of the Department of Irrigation in the 1910s sets the tone for the government's attitude towards water resources for many decades. The Department's surveyors went out to measure up land for irrigation schemes and chart some of South Africa's water resources in great detail (Gouws and Botha, 2003).

The Western Districts Game and Trout Protection Association represents angling interests in the Western Cape until 1931, when it is reconstituted as the Cape Piscatorial Society. The first fish hatchery is set up in Newlands (near Ohlsson's Brewery), and is later moved to Jonkershoek near Stellenbosch.

The University of Cape Town (UCT) and the South African Museum (SAM) are the early centres of gravity in the development of marine and freshwater fish work. John D. Gilchrist, who had previously been Government [marine] Fisheries Officer, becomes Professor of Zoology at UCT in 1908. He and his assistant, Mr WW Thompson of the SAM, produce a catalogue of the freshwater fishes of South Africa in 1913-1917 (Skelton, 1993). These publications are followed by K.H. Barnard's work on the taxonomy of South African fishes, especially those of the south-western Cape in the 1930s and 1940s. At about the same time, Barnard (of the South African Museum) began his studies on the taxonomy of a wide variety of aquatic invertebrates, both marine and freshwater (see **Section 1.5.2**). During the 1920s, Sydney Hey undertakes a series of fish surveys, looking in particular for waters that were suitable for the introduction of trout and he later writes a book on trout rivers (Hey, 1924) and another on the suitability of rivers for introduction of trout (Hey, 1926). Hey also documents the various types of organisms that he finds in the streams that he examines; these studies probably represent the first systematic biological surveys of South African rivers. Sydney's son, Dr Douglas Hey, works on the cultivation of trout in the 1930s and completes a PhD on this topic in 1938 (see Hey, 1939), signifying a continued focus by inland fisheries departments (the forerunners of provincial Nature Conservation departments) on the stocking of wild rivers with alien fishes, particularly bass and trout. Douglas Hey later becomes the Director of Nature Conservation in the Cape Province and the active role of the Cape Provincial Department of Nature Conservation in stocking rivers with alien fish species continues pretty much until his retirement in 1979.

Following the establishment of the Union Department of Irrigation in 1912, the construction of large water storage dams takes off in South Africa. The department is an amalgamation of the Cape and Transvaal provincial departments of irrigation, which had been established in 1904 after the South African War (1899-1903). In that same year significant legislation is passed, namely the Irrigation and Conservation of Waters Act (Act No. 8 of 1912). The law had three main objectives: to regulate the use of water in rivers and streams; to provide the judicial machinery required to define water rights, settle disputes and grant servitudes and permits; and to promote the development of irrigation, mainly through the construction of dams and water conveyance infrastructure (Union of South Africa, 1914). The Act is also significant as it concretes irrigation agriculture's domination as the top priority for government as far as water use is concerned (Tempelhoff, 2008). The first Director of Irrigation was Francis Edgar Kanthack, who comes to South Africa in 1906 to take up the position of Cape Director of Irrigation. Of German descent, Kanthack was born and schooled in Britain, and like many of the first engineers of the South African Irrigation Department gained his knowledge of engineering on the Indian Punjab (Bozzoli, 1997).

The first 'golden era' of dam building follows with the construction of notable large dams such as Hartbeespoort, Kamanassie, Van Ryneveld's Pass (now Nqweba), Lake Mentz (now Darlington), Vaal Barrage, Lake Arthur, Grassridge, Brandvlei and Bon Accord dams. The main objective of all of these dams is to supply water for irrigation and, while some form of hydrological survey is undertaken prior to their construction this is mainly concerned with economic rather than environmental considerations. Apart from the information gained from early river flow gauges almost nothing is known (at least within the Department of Water Affairs) about the rivers of South Africa.

World War I curbs capital expenditure on bulk water infrastructure somewhat, but dam building takes off again in 1929, this time as a result of the Great Depression. The construction of large dams and irrigation schemes is seen by the government of the day as a way of relieving white unemployment, although large numbers of labourers of other races are also later employed. Notable projects undertaken during this period include the Vaal Dam and Vaalharts schemes on the Vaal River, Buchuberg on the Orange River, Loskop Dam on the Olifants River and the Pongolo scheme in Natal. On some of these schemes, such as Buchuberg on the Orange River, little to no firm planning takes place prior to Parliament's announcement of the schemes, apart from basic surveying in some cases. The Irrigation Department has to draw up engineering designs in haste – sometimes when construction teams were already on site (Union of South Africa, 1931)

Groundwater sources are investigated for a long time in South Africa, partly for stock watering and partly for industrial use, particularly in mines. The Department of Mines produces a long series of memoirs (Geological Surveys of the Union of South Africa), documenting, among other things, many of South Africa's hot springs (Kent, 1949) and wetlands, as well as the nature and chemical character of several groundwater sources across the country (Bond, 1946).

2.3 Institutional landscape

During the early part of the 20th century, aquatic research in South Africa is limited to the sporadic efforts of a few individuals working in universities or museums. After 1910, when the former Republics of the Transvaal and the Orange Free State are combined with the British Colonies of the Cape of Good Hope and Natal to form the Union of South Africa, the new government plays an increasingly significant role in providing support for research. Initially this support is oriented primarily towards the production and processing of raw materials by the agricultural, silvicultural, mining and fishing industries. Government mechanisms for the support of industrial and university research are largely lacking (Kingwill, 1990).

Academic and student life during the very early 1900s is illustrated by the account of the development of Zoology at Rhodes University (Hodgson and Craig, 2005). A course in Biology (discontinued in 1914 but re-established in 1971) is offered in collaboration between the Departments of Zoology and Botany, and even a course in Applied Biology under the progressive leadership of Professor J.E. Duerden. Professor Duerden is the first incumbent of the Chair of Zoology at the then Rhodes University College, established in 1905. His annual salary at the time is £500, of which £150 is paid by the Albany Museum.

During these early years, male and female students had to enter the main building of the college though different entrances and are not allowed to smoke in the college precincts except in the men's common room. Academic dress has to be worn during lectures. The registration fee for a Bachelor of Arts degree in science is £5.5s per term during the 1910s and a laboratory fee of 10 shillings is introduced in the 1920s (Hodgson and Craig, 2005).

Although not directly related to aquatic science, it is interesting to note that some of the earliest zoological research at Rhodes has a distinctly applied character. To this end, Professor Duerden shifts his attention from his earlier research on corals to address practical issues faced by the ostrich feather industry. He becomes a world authority on ostriches with research covering morphology, formation of feathers, husbandry, genetics and behaviour. With the advent of World War I, demand for ostrich feathers ceases and the industry slumps. Professor Duerden then turns his attentions to the Merino wool industry and directs his research to answering practical issues in wool production (Hodgson and Craig, 2005).

World War I (1914-1918) results in an increased awareness of the need for organised research in support of technological development. In response, Britain establishes a Department of Scientific and Industrial Research (DSIR) in 1916. The Commonwealth countries Canada (1916) and Australia (1926) follow the British example and set up organisations for scientific and industrial research based on the DSIR model. South Africa is the exception, in spite of such proposals by the then Scientific and Technical Advisor to the Government, Dr H.J. van der Bijl (Kingwill, 1990).

A large part of this early era is characterised by extreme events: World War I (1914-1918), the Spanish flu epidemic (1918-1920), and World War II (1939-1945) are times of severe human hardship and result in many millions of deaths. In the meantime, the Wall Street Stock Exchange crash in October 1929 initiates a decade of global recession. The financial hardship of the 1930s extends to academic life in South Africa, to the extent that Rhodes University College freezes the position of Professor of Zoology upon Professor Duerden's retirement in 1932. In the same year, all staff have a choice of accepting either an 8% salary cut or loss of employment (Currey, 1970, as cited by Hodgson and Craig, 2005).

The 'positive' impact of research on military operations during World War II – for example in the development of radar, sonar and nuclear fission – leads to a widespread increase in the support for scientific research. Immediately after World War II, industrialised nations continue to invest liberally in science for peaceful applications.

During and directly after World War II, universities are more formally contracted to undertake research as a service to society in exchange for public funding. Although largely allowed to conduct research of their own choice, it is assumed that the resulting knowledge will support military security, public health and economic development. The scientific spirit of that time is reflected in a 1944 statement by Franklin Roosevelt:

> "*New frontiers of the mind are before us, and if they are pioneered with the same vision, boldness, and drive with which we have waged this war we can create a fuller and more fruitful employment and a fuller and more fruitful life*".

Perceptions of the role of science and technology in development were rather optimistic, shaped by the 'linear innovation model' whereby a direct relationship is assumed between scientific research, technology innovation, improved productivity and economic growth. An influential report (*Science: the Endless Frontier*) commissioned by Roosevelt entrenches a number of maxims, notably that:

- A defining role of basic research is to find general physical and natural laws to push back the frontiers of fundamental understanding – it is essentially performed without thought of practical applications for the final research outcomes.
- Advances of basic research will over time be converted into technologies through the process of innovation and the nation will recapture its investment in research in the form of technological benefit (assuming a linear relationship).
- A direct relationship will exist between the production of scientific knowledge, industrial progress and national competitiveness (Bush, 1945).

Following the notion of a positive linear relationship between research investment and economic benefit, scientific research would lead directly to technological innovation, improved productivity and economic growth. Governments are happy to invest in scientific capacity to produce discoveries and inventions. Funding for universities soars and national research councils are viewed as vehicles for enhancing technology transfer and promoting priority sectors such as manufacturing, agriculture and mining.

South Africa's direct involvement in and experiences of World War II triggers a significant change of attitude towards science. At the same time, South Africa is entering its own industrial revolution, which is associated with an expanding economy diversifying from its previous purely agricultural and mining focus. The country is faced with a variety of technological problems for which solutions are urgently required. In response, the Prime Minister of the day, General J.C. Smuts, appoints Dr B.F.J. Schonland as Scientific Advisor to the Prime Minister in January 1945. Dr Schonland's first task is to design plans for a national research organisation, which results in Parliament passing a Bill for the establishment of the Council for Scientific and Industrial Research (CSIR). Drafting of the Bill is preceded by consultation with government departments, universities, industry, scientific societies and leading overseas scientists. The CSIR is formally established on 5 October 1945 as a 'body corporate' outside the Public Service. In defence of the latter, Schonland argues that research required a different kind of organisation, with a relatively high degree of freedom and flexibility and an ability to respond rapidly to the demands of changing circumstances. The low rate of pay and promotion by seniority associated with the Public Service would also not be conducive to creative research (Kingwill, 1990).

During this period, developments in limnology are dominated by scholars from Europe and North America. Apart from Professor J.L.B. Smith at Rhodes University, an Associate Professor of organic chemistry in the Chemistry Department, there are no prominent academic ichthyologists at any South African university. By 1945, 86% of the currently valid fish species in South Africa have been described by overseas taxonomists, such as Dr George Boulenger at the British Museum of Natural History in London (Skelton, 1997).

While limited funding is available for research, researchers had almost complete freedom to pursue their own research interests. This is demonstrated by Dr J.H. Day's switch from marine to estuarine surveys because "*research funds were very limited and it was cheaper to make an ecological survey of estuaries than to hire a fishing boat*" (Day, 1977 as cited in Whitfield, 1998). Another example is provided by J.L.B. Smith, a Chemist by training (PhD in Chemistry from Cambridge University) and trade (Associate Professor of Organic Chemistry at Rhodes University College), whose love for angling directs his attentions towards the scientific study of fishes.

To describe new species, researchers had to rely on, or develop, their artistic abilities to make drawings or paintings from specimens that were collected. Margaret Smith, JLB Smith's wife, did a lot of 'Fishy' Smith's artwork.

3 THE MIDDLE YEARS (1946-1979)

3.1 Chronology of key events

1946 – Dr Keppel Barnard is appointed as Director of the South African Museum in Cape Town, having already been Acting Director in 1924 and from 1941-1946.

1946 – The newly founded CSIR awards J.L.B. Smith a Research Fellowship in Ichthyology at a rate of £800 per annum for three years (Pote, 1996).

1946 – A dentist, T. Ockerse, conducts the first surveys of fluoride in water supplies and assessed the incidence of dental fluorosis in humans (Ockerse, 1946).

1947 – Dr E. M. Van Zinderen Bakker arrives in South Africa from the Netherlands to join the Department of Botany of the University of the Orange Free State.

1947 – Bob Crass publishes his MSc thesis on the Mayflies of Natal and the Eastern Cape, the first South African monograph on this group of aquatic insects.

1948 – Official (promulgated) introduction of the Apartheid policy of statutory racial differentiation and segregation, formalizing the segregationist policies of previous governments, will have fundamental effects on the management and use of South Africa's aquatic resources. The Bantu Education Act of 1953, especially the notorious statement, "*What is the use of teaching the Bantu child mathematics when it cannot use it in practice?*", will have dire consequences for the scientific and mathematical education of the majority of South Africans for decades to come, and will ensure that there is a completely inadequate pool of scientists in South Africa by the end of the 20th century.

1948 – John Day is appointed as Professor of Zoology at the University of Cape Town.

1951 – The Orange Free State Goldfields Government Water Scheme is completed. This is the first large bulk water infrastructure project undertaken by government that is not intended for irrigation purposes. It also signals the start of the era of construction of large government water transfer schemes, mostly to bring water to drier catchments experiencing a steep increase in water demand due to South Africa's rapid post-war economic growth.

1953 – The brothers Eugene Pleasants Odum and Howard Thomas Odum publish the first ecology textbook, *Fundamentals of Ecology,* widening exposure to trophic dynamics and the ecosystem concept (Odum, 1953).

1956 – The Department of Irrigation is transformed into the Department of Water Affairs, with the promulgation of the Water Act (Act No. 54 of 1956). This transition was preceded by, and was as a result of, the recommendations contained in the report by the Hall Commission of Enquiry into the state of water in South Africa. The recommendations of this Commission laid the groundwork for South Africa's rapid economic growth up to the end of the 1960s, despite the country's growing political isolation from most of the rest of the world as a result of the Apartheid policy.

1956 – South Africa's first Water Act (Act No. 54 of 1956) introduces numerical standards for the quality of treated effluents that may be discharged into a surface water resource; these standards are to be enforced by the Department of Water Affairs. Effluents have to be treated to meet the uniform effluent standards and then discharged into the 'stream of origin' so that natural purification processes can further improve the water quality and enable the water to be reused safely by downstream users. This approach reflects the growing realization that water supplies are becoming increasingly scarce as demands for water grow and water quality continues to deteriorate.

1957 – Publication of G. Evelyn Hutchinson's first volume of *A Treatise on Limnology: Geography, Physics and Chemistry* (Hutchinson, 1957).

1958 – A.D. Harrison publishes important papers on the Great Berg River (Harrison, 1958a, 1958b) and then, with J.F. Elsworth, publishes a monograph on the hydrobiology of the Great Berg River (Harrison and Elsworth, 1958); K.M.F. Scott contributes a section on the Chironomidae collected during the study (Scott, 1958).

1958 – Publication of an early paper on snail ecology and the medical significance of snails in South Africa (De Meillon *et al.*, 1958).

1958 – The Water Treatment Division of the CSIR's National Chemical Research Laboratory becomes the National Institute for Water Research with Dr G.J. (Gerrie) Stander as its founding Director. A major focus of the work carried out by this institute is on processes for treating polluted water to provide potable water and water for industrial uses. The work on effluent treatment and reclamation for potable water culminates in the implementation of the Windhoek Reclamation Plant in 1968, which treats domestic sewage and recovers potable water for supply to the City of Windhoek – a world first.

1960-1965 – W.D. Oliff produces a number of papers on the Hydrobiology of the major Rivers in Natal.

1962 – Arthur Harrison publishes his work on the vleis of the Cape Peninsula (Harrison, 1962).

1962 – General effluent standards, and the associated recommendations for the analysis of the different parameters, are drawn up by the South African Bureau of Standards, and promulgated.

1962 – Rachel Carson's *Silent Spring* is published (Carson, 1962). This book is widely credited with helping launch the environmental movement.

1963 – The Limnological Society of Southern Africa is founded in Grahamstown with Arthur Harrison as the first president.

1963 – Professor Brian Allanson is appointed to the Chair of Zoology and Entomology at Rhodes University. Formerly head of the Limnology Division at the National Institute for Water Research in Pretoria, his appointment leads to a significant emphasis on aquatic science at Rhodes University.

1964 – The International Biological Program (IBP) is implemented in an effort to coordinate large-scale ecological and environmental studies. Brian Allanson later secures support for a limnological study of Lake Sibaya in northern Natal.

1964 – Institute for Freshwater Studies (IFS) is established by the Council of Rhodes University, Grahamstown. Professor B.R. Allanson is the first Director.

1965 – Prof B.R. Allanson and the staff of the IFS at Rhodes University begin field studies at Lake Sibaya in Tongaland, northern Natal.

1965-1966 – The first biological research expedition to sub-Antarctic Marion Island takes place under the leadership of Professor E.M. van Zinderen Bakker. The studies conducted during this expedition are later published in an important monograph (van Zinderen Bakker *et al.*, 1971).

1966 – The launch of the Commission of Enquiry into Water Matters, which would publish its final report in 1970 (CEWM, 1970). This document leads directly to the formation of the Water Research Commission (WRC) and the Hydrological Research Institute (HRI) at the Department of Water Affairs. This report also focuses increased attention on the need to ensure the security of water supplies and their quality (fitness for use) into the future, as well as improving relations with neighbouring states that share river basins with South Africa.

1967 – Publication of G. Evelyn Hutchinson's second volume of *A Treatise on Limnology: Introduction to Lake Biology and the Limnoplankton* (Hutchinson, 1967).

1967 – Publication of Rex A. Jubb's *Freshwater Fishes of Southern Africa* (Jubb, 1967).

1967 – Building of the Lake Sibaya field station commences. The station will later be closed as a result of serious flooding in 1976 (Hodgson and Craig, 2005). On one visit the Natal Parks Board advises that their two fisheries officers Pike and Rowe will join the first research trip to the new field station.

1967 – Rand Afrikaans University was formed in Auckland Park, Johannesburg. Inland aquatic research programmes start in the Department of Zoology the next year, led by Professor H.J. Schoonbee, formerly of the Durban office of the CSIR's National Institute for Water Research.

1967 – Willem Scott produces his MSc thesis on culturing algae in different water samples, investigating synchronous algal cultures and the effects of water quality on algal growth. He moves to Pretoria to join the NIWR and works on algal cultures and the ecology of *Microcystis* in eutrophic Transvaal impoundments. Daan Toerien introduces the Provisional Algal Assay Procedure (PAAP) that he had contributed to developing while in the USA as a way to 'measure' the eutrophication potential of freshwaters.

1968 – F.M. Chutter identifies simuliids as problem pest species in the Vaal River; the species responsible for large outbreaks with severe economic consequences for livestock farmers is named *Simulium chutteri* Lewis, 1965 in his honour.

1968 – Rhodes University creates the J.L.B. Smith Institute of Ichthyology to honour and continue the academic work of JLB Smith (Pote, 1996).

1968 – Tol Pienaar produces the first version of a book on the fishes of the Kruger National park (Pienaar, 1968). A second, revised edition of this useful publication appears ten years later (Pienaar, 1978).

1969 – The Kat River Dam is completed in the Eastern Cape. This is the first large dam in the country where engineering calculations and designs were undertaken by computer.

1970 – Publication of the first scientific treatise of lotic ecosystems, *The Ecology of Running Waters* (Hynes, 1970).

1970 – The Freshwater Institute of Rhodes University begins the Swartvlei Project under the direction of Brian Allanson. Clive Howard-Williams (who previously worked on Lake Chilwa in

Malawi) and Richard Robarts (from Canada) join the Freshwater Institute at Rhodes to work on the Swartvlei Project.

1971 – The Water Research Commission is established with Dr Gerrie Stander, previously founder Director of the NIWR, as first Vice-President and Executive Officer. The WRC provides a key mechanism for funding and reviewing all aspects of water research in South Africa.

1971 – Floppy disks, a magnetic data storage medium invented at IBM, become commercially available to the public.

1971 – The Gariep Dam (formerly known as the Hendrik Verwoerd Dam), the largest reservoir in the country, is completed on the Orange River as part of the first phase of the Orange River Project.

1971 – The Orange River Project – funded by the forerunner to the Co-operative Scientific Programmes unit at CSIR, with inputs from the Department of Water Affairs – is set up to carry out scientific studies on the limnology of the Gariep Dam. Researchers from the (then) University of the Orange Free State (Professor E.M. van Zinderen Bakker, Peter Stegmann, Pieter Keulder, Johan Grobbelaar) and Rhodes University (Professor E.S. Twyman, Peter Ashton) conduct research on the physical, chemical and biological characteristics of the reservoir and its inflowing rivers, plus the aquatic plants in these rivers.

1972 – Start of the National Programme for Environmental Sciences (NPES) at CSIR, with a strong emphasis on ecosystems. Over time, NPES studies of inland water ecosystems include water requirements (Pongolo floodplain), eutrophication (Hartbeespoort and other Highveld impoundments), nutrient cycling (Midmar Dam), and turbidity (Wuras and PK le Roux). These research programmes provide the opportunity for students to conduct research for higher degrees and who become the source for competencies required by government, research institutions and universities.

1972 – The Hydrological Research Institute opens on 20 October 1972 with Ms J.S. Whitmore as founding Director, at this time one of the highest-ranking posts attained by a woman in the Public Service (See details in **Appendix C**).

1972 – Marjorie Scott becomes the first curator of the national invertebrate collection, at the Albany Museum in Grahamstown.

1972 – Charles Breen and Jan Heeg at the University of Natal in Pietermaritzburg begin research on the Pongola river floodplain.

1973 – Peter King undertakes the first survey of Zeekoevlei near Cape Town.

1973 – The Pongolapoort Dam is completed in KwaZulu-Natal. Phelines, Coke and Nicol give a presentation to the International Commission on Large Dams (ICOLD) Conference on some of the biological consequences of the damming of the Pongolo River. This was one of the first dams in the country for which comprehensive environmental flow research is undertaken.

1973 – The University of the Free State establishes a research laboratory at Gariep Dam as part of the Orange River Project, which was funded by the National Programme for Environmental Sciences (NPES) unit at CSIR.

1974 – The Institute for Freshwater Studies (Rhodes) opens a research station at Swartvlei.

1974 – The first phase of the Thukela-Vaal Transfer Scheme, including the construction of the Spioenkop Dam, is completed.

1974 – The University of Natal establishes the Pongola Floodplain Research Station at Jozini from where research on the Pongola floodplains is carried out.

1975 – Publication of G. Evelyn Hutchinson's third volume of *A Treatise on Limnology: Limnological Botany* (Hutchinson, 1975).

1975 – CSIR establishes the Co-operative Scientific Programmes (CSP) in recognition of the need for collaborative research. It builds on the National Programme for Environmental Sciences (NPES) launched in 1972.

1975 – The NIWR starts a three-year study of phytoplankton population dynamics and succession patterns in Rietvlei Dam – a eutrophic reservoir that provides about 15% of Pretoria's water supply. These studies include the first attempts to understand the influence of hydrological processes on nitrogen transformations and nitrogen fixation by phytoplankton in a South African reservoir (Walmsley and Ashton, 1977; Ashton, 1979; 1981).

1977 – The large Vanderkloof Dam (formerly known as the PK le Roux Dam) is completed as part of the Orange River Project carried out by the Department of Water Affairs.

1978 – Publication of *Inland Water Ecosystems in South Africa: A review of research needs,* a South African National Scientific Programmes report (Noble and Hemens, 1978) provides the first comprehensive overview of the research needed to understand and manage inland waters in South Africa.

1978 – At the request of the WRC, the NIWR carries out a comprehensive evaluation of the chemical control programme against water hyacinth (*Eichhornia crassipes*) on Hartbeespoort Dam. Though the plant was first noticed in this reservoir in 1958, the absence of decisive action allowed the water hyacinth infestation to increase to 1,200 hectares in extent, equivalent to two-thirds of the surface area of the reservoir. The Department of Water Affairs carry out the chemical control programme using the systemic herbicide terbutryne and this is entirely successful (Ashton *et al.*, 1979; Scott *et al.*, 1979). However, the absence of floating water plants and the continued input of high nutrient loads to the reservoir results in a massive *Microcystis* bloom developing (Scott *et al.*, 1980).

1978 – The Ministerial Palmiet Advisory Committee is set up to discuss the future of the water resources of the Palmiet River (Western Cape) and their role in improving the reliability of water supplies to the City of Cape Town. This event probably represents the first symbolic 'victory' for those individuals and institutions concerned with environmental issues over what was then perceived as the "dam-at-all-costs" approach. While the Palmiet has still not been dammed at this stage, future plans to secure the water supplies for the Cape Town metropolitan area include the construction of water transfers from the Palmiet system.

1979 – Margaret Thatcher and the Conservative Party win the general Election in the United Kingdom, and continue promoting cordial relations with South Africa.

1979 – The first international conference on African Limnology is held in Nairobi, Kenya under the auspices of SIL and UNEP. South African limnologists participate prominently both in organizing the conference and in writing up its proceedings.

1979 – The second phase of the Thukela-Vaal Transfer Scheme, including the construction of the Sterkfontein and Woodstock dams as well as the Driel Barrage, is completed. This is one of the first large water schemes where environmental considerations influenced the design and engineering aspects of the project.

1979 – The so-called '21 Dams Report' is published by the National Institute for Water Research (NIWR), providing brief descriptions of the physical, chemical and biological characteristics of important water storage reservoirs in the Transvaal, Natal and Eastern Cape provinces (Butty and Walmsley, 1979).

1980 – The NIWR publishes a second report on the physical, chemical and biological characteristics of important water storage reservoirs (Walmsley and Butty, 1980). The causes of eutrophication and the eutrophication status of each reservoir is the primary focus of the report.

3.2 Individuals and topics of note

The 1930s saw an interesting development involving a South African aquatic animal – *Xenopus laevis,* the clawed toad or platanna. Lancelot Hogben, a British experimental physiologist and medical statistician, became Professor of Zoology at the University of Cape Town in 1927. Working on the physiology of amphibians, he noticed that various hormones caused female *Xenopus* to ovulate. Being a very good – and extremely curious – scientist, Hogben follows up his finding and soon realized that it might be possible to use *Xenopus* as a means of testing for pregnancy in humans. (Up to this time, it was no more than guesswork as to whether a woman was pregnant or not). Harry Zwarenstein, a young postgraduate student, works in Hogben's lab in Cape Town, learnt something of his techniques.

After Hogben had returned to the UK in 1930, Zwarenstein and a colleague, Hillel Abbe Shapiro, try to culture *Xenopus* and report back to Hogben that this was almost impossible to do. Hogben soon (1933) invites them both to London to visit his lab and observe his own rearing techniques, which are very successful. Hogben and his team publish several papers on the physiology and rearing of *Xenopus* but Hogben did not want to publish on his proposed use of the animal for pregnancy testing until he was quite sure of the practicability and reliability of the test. Shortly after they returned to Cape Town, Shapiro and Zwarenstein did the unforgiveable and incurred the understandable wrath of Hogben. They had recently performed pregnancy tests on freshly caught frogs and published a note to that effect in the *Transactions of the Royal Society of South Africa* (Shapiro and Zwarenstein, 1934), shortly before one of Hogben's assistants published a more definitive report in *Nature* (Bellerby, 1934). Incidentally, the 'frog test' became *the* pregnancy test for many years. Hogben was notoriously eccentric. John Day used to tell the story of the occasion on which Hogben was had up for drunken driving in the UK. In those days there were no tests for blood alcohol levels and conviction relied very largely on eyewitness accounts of the behaviour of the accused. Hogben is said to have found several colleagues who testified in court that one could not tell the difference between Lancelot Hogben drunk and Lancelot Hogben sober.

On the aquaculture front, Douglas Hey produces a research paper on the artificial culture of *Xenopus* (Hey, 1949), a book on fish keeping in ponds and aquaria (Hey, 1952) and a book on practical freshwater fish culture (Hey, 1971). The Jonkershoek hatchery of the Cape Province's Nature Conservation agency plays a leading role in investigating the culture requirements of alien fish species for wider introduction as sport angling fishes across the Cape Province. Trout, and alien freshwater ornamental fishes, are kept at Jonkershoek and supplied on demand.

'AC' (Arthur Cecil) Harrison, Arthur Desmond Harrison's father, writes valuable early articles on indigenous Cape fishes for *Piscator*, journal of the Cape Piscatorial Society. His early articles (*e.g.* Harrison, 1938; 1952; 1959) on the distribution of various redfin minnows, Cape kurper and whitefish provide valuable information on the historical distribution of these species.

Work by K.J. van Rensburg in the 1960s on the indigenous freshwater fishes of the Olifants-Doring system leads to a ground-breaking research report (Van Rensburg, 1966) for the Cape Department of Nature and Environmental Conservation (CDNEC) staff, in that it triggers a focus on indigenous fishes and shows the emerging conservation crises of fishes in rivers draining the fynbos vegetation (Gaigher, 1973; Gaigher *et al.*, 1980).

Kas Hamman and Stewart Thorne initiate regular surveys and monitoring of the status of indigenous fish populations in aquatic systems of the former Cape Province. The information gathered in these surveys makes a valuable contribution to our knowledge of the distribution of the various species and contributed significantly to the freshwater fish collections at the Albany Museum and the former JLB Smith Institute for Ichthyology. It highlights the various threats to our native fishes and provides information for the various Red Data publications for freshwater fishes.

The period from the late 1940s to the late 1970s is marked by the construction of several hundred water storage impoundments (dams) across the country (**Figure 2**). This has been referred to as the "hydraulic mission" of the country's water resource management authorities, the primary purpose of most dams being to supply water for irrigation and water to expanding industries and urban centres.

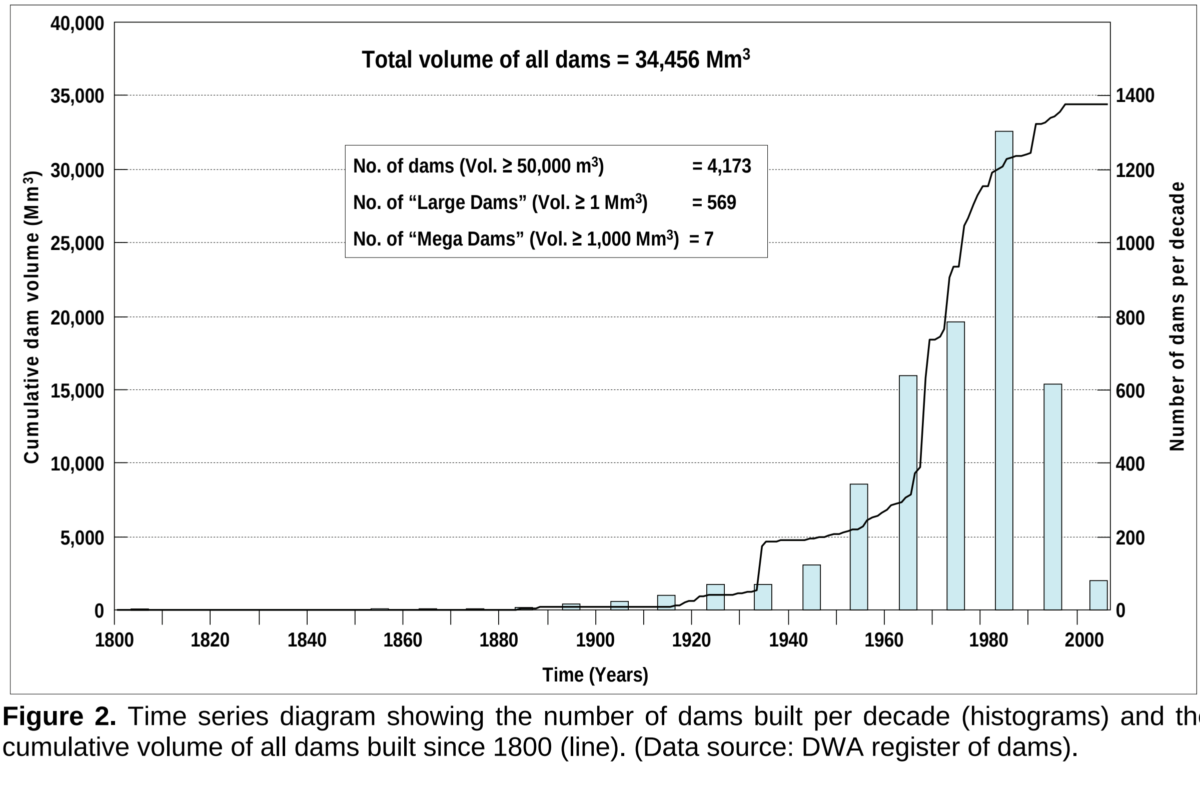


Figure 2. Time series diagram showing the number of dams built per decade (histograms) and the cumulative volume of all dams built since 1800 (line). (Data source: DWA register of dams).

South Africa now has a total of 4 173 water storage dams, each with a capacity greater than 50 000 m^3. Of these dams, 569 are classified as "Large Dams" and 7 are considered to be "Mega Dams" (**Figure 2**). The combined capacity of all the impoundments listed in the dam register at the Department of Water Affairs is 34 456 Mm^3; in addition, there are also approximately 150 000 smaller farm dams in the country and these contribute an estimated additional storage capability of 3 000 Mm^3. In combination, the capacity of South Africa's dams is therefore estimated to be about 37 000 Mm^3, equivalent to approximately 73% of the country's mean annual runoff. This represents an extraordinarily high percentage of runoff capture, a proportion unmatched by any other country in the world.

From a limnological perspective, the hydraulic mission provides limnologists with a new kind of ecosystem – artificial lakes – to work on, because the interior of the country is almost entirely devoid of natural lakes.

Brian Allanson arrives in South Africa from Sri Lanka where he completed his schooling before obtaining his BSc degree at the University of Natal and later a BSc (Hons), MSc and PhD degrees at UCT, before moving to the NIWR in Pretoria to lead the Hydrobiology (Limnology) Division. Brian Allanson publishes his PhD *verbatim* in the journal *Hydrobiologia*.

Tol Pienaar, working in the Kruger National Park (KNP), conducts important early work on the fish species found in all the KNP river systems and publishes two useful books on the fishes of the KNP (Pienaar, 1968; 1978).

Amy Jacot Guillarmod (1911-1992) (http://en.wikipedia.org/wiki/Amy_Jacot_Guillarmod) studies plants, including aquatic ones, especially in Lesotho from 1940-1957.

John Day was the main pioneer in estuarine work with many references from the 1950s.

Dr B.J. Cholnoky arrives from Hungary just after World War II, working first with E.M. van Zinderen Bakker at the University of the Orange Free State, then with the NIWR from the mid-1950s. Cholnoky develops a large collection of diatoms from across South Africa and elsewhere on the continent, producing one of the first water quality maps for South Africa based on the correlations he had found between the distribution of certain diatom species and the water quality at these localities. Cholnoky refers to Hartbeespoort Dam as "*a maturation pond*" in the 1950s. His wife, Dr K. Cholnoky-Pfannkuche, also works at the NIWR, studying the taxonomy of cyanobacteria and diatoms, and deformities in diatom frustules relative to water quality.

Between 1950 and 1970 the National Institute for Water Research (NIWR) of the CSIR undertakes a number of surveys of the fauna, flora and physico-chemistry of many South African rivers. The earliest and most comprehensive study is that on the 'Great' Berg River. Arthur Harrison and Marjorie Scott work on the invertebrates and Jack Elsworth on water chemistry, producing four papers, all published in the *Transactions of the Royal Society of South Africa* in 1958. The first, by Harrison and Elsworth, (Harrison and Elsworth, 1958) is one of the earliest comprehensive studies on a river anywhere in the world, while Marjorie Scott's paper (Scott, 1958) is one of the few on the chironomids of any South African system. Harrison and Scott are mentioned elsewhere in this document; Jack Elsworth lectures in chemistry at the University of Cape Town for many years and dies in 2003. Other NIWR surveys of rivers are undertaken on the Tugela River by Hendrik Schoonbee and Bill Oliff, the Olifants and Jukskei rivers by Brian Allanson and Joris Gieskes, and the Mgeni and Vaal rivers by Mark Chutter.

Ian Gaigher surveys and collects fishes from most of the rivers within the old Transvaal Province whilst working for the Transvaal Provincial Administration (TPA) at their Lydenburg fisheries station. Gaigher then moves, first to the University of Fort Hare, then to Cape Nature Conservation, then to the University of the Orange Free State, and finally to the University of Venda.

Others who worked for TPA at the Lydenburg fisheries station include: Piet Mulder, Garth Batchelor, Neels Kleynhans and Johan Engelbrecht. At the time, Lydenburg is regarded as a centre of excellence for fisheries and fish biogeography work.

In 1960 Wits University starts the Nuffield Lake Kariba Research Station at Sinamwenda to conduct limnological research on this newly formed man-made lake. The initiative is led by Professor B.I. Balinsky (an embryologist who later became interested in insects, mostly microlepidopterans but also plecopterans and odonates). The Lake Kariba Fisheries Research Institute sited at Kariba town is initiated by the FAO and is later taken over by the Department of National Parks and Wildlife Management when FAO withdrew its support following Rhodesia's Unilateral Declaration of Independence from Britain. The Nuffield Lake Kariba Research Station is later operated by the then University College of Rhodesia (originally part of the University of London), and later the University of Rhodesia (now the University of Zimbabwe). Studies also start at the University of Rhodesia on *Salvinia molesta* (Kariba weed) under Dave Mitchell, following the massive invasion of Lake Kariba by this weed after the formation of the lake in 1959. The station is now the University of Zimbabwe's 'University Lake Kariba Research Station'.

After the closure of the Sibaya research station because of flooding, the Rhodes University limnological effort is transferred to Lake le Roux, a large silt-laden reservoir on the Orange River, where a multi-disciplinary research programme is carried out until 1984.

Whilst much of the aquatic research from 1965 to 1980 is ecosystem-based, a number of workers publish benchmark autecological studies on single species. Prominent examples include the work of Burke Hill on *Upogebia africana* and *Scylla serrata* (*e.g.* Hill and Allanson, 1971; Hill, 1975; 1977); Ticky Forbes on *Callianassa krausii* (*e.g.* Forbes, 1973); Stephen Blaber on *Rhabdosargus holubi* (*e.g.* Blaber, 1973; 1974); Tony Ribbink on cichlid fish (*e.g.* Ribbink, 1977), Rob Hart on the freshwater copepod *Pseudodiaptomus* (*e.g.* Hart, 1977) and Mike Bruton on *Clarias* (*e.g.* Bruton, 1979).

Work on Lake Sibaya is essentially the only South African contribution to the IBP-PF, which was regrettably approaching its closing phases at the time. There are a number of "firsts" for South and indeed southern African limnology. Those dealing with plankton population dynamics and production, and on the biology and ecology of the benthic shrimp *Caridina* in littoral habitats in the lake, are outlined in more detail below. Other, mostly offshore (deeper-water) benthic invertebrate studies are undertaken by Robin Boltt. Brian Allanson and his co-workers have an important paper published in *Nature*, describing the existence of 'estuarine' taxa in a freshwater system (Allanson *et al.*, 1966). The detailed studies conducted at Lake Sibaya yield several novel insights into the structure and functioning of an inland freshwater system, including:

- The first detailed multi-annual study of phytoplankton periodicity (Hart and Hart, 1977), as well as first studies of pelagic primary production in any South African lake or reservoir (Allanson and Hart, 1975).
- The first detailed analysis of population dynamics and production of a zooplankter, of particular relevance in the IBP data arsenal as it provided one of the few studies in a subtropical lake (Hart, 1981a; Hart and Allanson, 1975), complementing some concurrent studies on tropical Lake George (Uganda) by Mary J. Burgis. Rob Hart recalls the first plankton sample that he had to analyze: no-one had informed him about sub-sampling. Having spent nearly three days continuously counting individuals in the sample, he embarked on his own short-cut approach – effectively a sub-sampling protocol familiar to those trained in plankton work. At the time, he knew nothing about plankton, having gone to university with his eyes set on a future in ornithology.

- A comprehensive study of diel vertical migration, and its implications in the biology of the migratory copepod (*e.g.* Hart, 1977; Hart and Allanson, 1976). This involved repeated net-haul collections of zooplankton over various depth strata, requiring repeated 24-hour-long stints anchored in the middle of the lake, and at other times trying to locate the station buoy at night, using horizon profiles. Nothing like GPS was available at the time.
- Studies on population dynamics and production of the freshwater shrimp, *Caridina nilotica* (*e.g.* Hart, 1980a, 1980b, 1981b, 1983; Hart and Allanson, 1981). The findings of these studies lay dormant for nearly two decades, until *Caridina* emerged as an organism of major prominence and functional significance in Lake Victoria, after the introduction of Nile Perch into the lake. Based on his knowledge of this shrimp in Sibaya, Rob Hart subsequently pursued some work on it in Lake Victoria, devising a novel technique to estimate *in situ* growth rates (Hart 2001; Hart *et al.,* 2003).

The monograph on Lake Sibaya (edited by Brian Allanson) appears to be the only such volume ever devoted to a coastal lake (Allanson, 1979).

George Begg's seminal works on the *Estuaries of Natal* and the *Wetlands of the Mfolozi Catchment* for the Natal Town and Regional Planning Commission (Begg, 1978, 1984, 1986, 1988) provide an important impetus for activities geared towards understanding the functioning and conservation status of these systems.

The Estuarine and Coastal Research Unit (ECRU) of the CSIR's National Research Institute for Oceanology (NRIO) carry out extensive studies on the estuaries of the Cape Province, producing an important series of reports – the so-called 'green reports'.

Chris Appleton publishes several papers on mollusc ecology and bilharzia during the 1970s. J.F. Prinsloo and J.A. van Eden produce a series of papers in the 1970s on the distribution of molluscs in Lesotho. Researchers at Potchefstroom University conduct several studies on the effects of water temperature on medically important freshwater molluscs (*e.g.* De Kok, 1973).

A study on the effects of large dams on downstream river water temperatures and the influence of water temperature on the distribution of bilharzia (Pitchford and Visser, 1975) provide evidence that lowered water temperatures inhibit vector snail populations.

Daan Toerien returns to South Africa after completing his PhD at the University of California and brought back a new understanding of eutrophication processes and the Provisional Algal Assay Procedure (PAAP) test on his return to the CSIR in South Africa. This assay forms the basis for new and expanding research on reservoir eutrophication processes. Daan's work has a profound effect on linking nutrient loading from rivers with eutrophication of impoundments and is responsible for the switch in research focus of CSIR aquatic scientists from rivers to impoundments (Toerien *et al.*, 1975; Toerien, 1977).

Graham Noble and Julian Hemens undertake a broad-scale classification of South African rivers and surveyed the needs for freshwater research across South Africa. Their results provide a benchmark for much of the early research on the conservation status of rivers, lakes, pans and wetlands (Noble and Hemens, 1978).

Richard Robarts arrives from Canada in November 1970, moving to the Zoology Department at Rhodes University to conduct PhD research on microbial processes in a coastal lake, Swartvlei, located between Knysna and Wilderness.

In 1967 Hendrik J. Schoonbee leaves the NIWR's Durban office – where he had been working on water quality in Natal rivers – and moves to the newly formed Rand Afrikaans University (RAU) as Professor of Zoology. His interests centre on water quality, toxicity and the use of capture-mark-release-recapture techniques for estimating fish populations, and he attracts several new research students to his rapidly expanding department. The research effort is concentrated on aquatic science in the then Transvaal province. The department starts focusing on fish and invertebrate population studies in the northern interior of South Africa and within ten years becomes well known for its research into fish populations of impoundments. Johann Hattingh starts with fish physiology at RAU in 1972, establishing basic values for health conditions and guidelines for transporting fish. Then in the 1980s, he starts work on bioaccumulation in wetlands, concentrating on the accumulation of metal ions in fish. In the following years, specific research areas are developed around the individual interests of the faculty, namely in the morphology, haematology, parasitology and population genetics of fish, and in ecotoxicology more generally.

The Watlings at the University of Port Elizabeth study the distribution of metal ions in estuarine sediments, initially in the estuaries closest to Port Elizabeth and then later more widely across South Africa.

Charl Bruwer enters the freshwater scene in 1974, joining the HRI at DWAF and working on the Phongola River downstream of the Pongolapoort Dam (Bruwer *et al.*, 1996).

Bryan Davies arrives in 1974 from the University Eduardo Mondlane in Maputo, Mozambique – first meeting up with South African limnologists at the 1974 SASAqS Conference in Bloemfontein, before moving to Rhodes University in Grahamstown.

During the late 1970s, work on turbid reservoirs is funded by Cooperative Scientific Programmes (CSP) through the National Scientific Programmes (led by Graham Noble and later Brian Huntley). In the early years of the CSP when research programme managers met at the CSIR, the President of CSIR always hosted them at lunch. This is influential in establishing a profile for aquatic science in South Africa. These studies provide a much improved understanding of turbid reservoirs. This is classic limnological work, first using only traditional field instruments and later incorporating isotope tracer studies. A series of integrated research programmes are conducted on lakes and impoundments, notably Gariep, Midmar, Pongola, St Lucia, Le Roux, Hartbeespoort, Wuras. These research programmes are closed down in the late 1980s when the CSP is incorporated into the Foundation for Research Development (FRD), which then splits off from the CSIR. This is an unfortunate development because most of the programmes have been highly successful. The South African Cooperative Scientific Programmes are the envy of the rest of the world at the time because they receive fairly continuous funding, there are good prospects for carrying out fundamental research, and funding is available for post-graduate students. All of these are things that make for good ecological science and are not very expensive.

Work on zooplankton in Lake le Roux (Vanderkloof Dam) fore-fronts international knowledge regarding the impacts of suspended sediment on zooplankton community structure and abundance, and especially on feeding biology. The first ever South African studies on zooplankton grazing rates *in situ* arise from a newly-designed apparatus (Hart and Christmas, 1984). A clearer understanding of the impacts of sediment content on zooplankton distribution also emerges from these studies. Controlled experimental examinations of the importance of food limitation or suspended sediment content on growth of zooplankters are also undertaken (Hart, 1991).

Rob Hart and Brian Allanson obtain their private pilot licences to enable them to shorten the travelling time between their university base (Rhodes University in Grahamstown) and their (then) area of research focus (Lake Le Roux on the Orange River). Jim Cambray remembers that limnological research during the late 1970s and early 1980 on the then PK le Roux Dam was not always easy, especially for researchers from Rhodes University. A staff member is always sent out to inspect the gravel runway for holes before they land their plane. One day, with Brian Allanson at the controls, Jim saw one wing dip low as the plane came in and thought: "*This is it!*" But, with a bounce or two on the gravel runway, all was well.

There were also some close calls on the water. Brian Allanson wanted to put in permanent buoys at each of the limnological stations. Ken Coetzee the local manager of the nature reserve made the large cement anchors that would anchor the buoys in place. Brian Allanson insisted that he would be on the pontoon and make sure buoy number 1 was correctly positioned. The team borrowed a large metal pontoon from Department of Water Affairs and loaded the first large cement anchor number on to it. Jim then secured one of the team's research boats to the pontoon and pulled it into position. Along with two of the staff members, Brian Allanson grabbed a metal stake at the side of the cement anchor and heaved; however, his stake came loose and over he went and disappeared under the large metal pontoon. Jim thought that this was the end. Either Brian would have hit his head on the pontoon floats or become entangled in the mooring cable. Jim was very proud of his staff (who could not swim) because they had the sense to run to the other end of the pontoon to see if Brian Allanson would come up instead of looking over the side where he had gone under. One must understand that this pontoon could not be stopped and had quite a forward momentum. Thankfully, up popped Brian's head and the staff members hauled him on board. Jim has a clear memory of Brian looking like a drowned rat standing on the pontoon dripping wet with his blue Canadian plaid jacket on. Jim managed to pull the pontoon back to shore and the students present did not see a thing and looked downwards and not at their dripping Professor. Brian had also lost his trademark golden half-frame reading glasses but thankfully not his life. That night he noted that the research funders of the time did not know the hardships of conducting research under field conditions.

Studies on zooplankton grazing impacts in Hartbeespoort were undertaken using an *in situ* grazing chamber based on Rob Hart's design. This work by Andrew Jarvis, then a PhD student under Rob Hart, also develops new knowledge about the disruptive effects of large colonial autotrophs (especially *Microcystis*) on the feeding of *Daphnia* in particular, and thus the regulatory role of these organisms in zooplankton species composition and seasonal succession, *via* differential susceptibilities to these effects (Jarvis *et al.*, 1987; 1988). These studies demonstrate the implausibility of using the now much-touted idea of biomanipulation as an eutrophication control option in systems dominated by *Microcystis* (Hart, 2006b). Decomposing *Microcystis* was expected to result in large bacterial populations, and the role of such bacteria as a food resource for zooplankton was also examined (and found to be rather trivial), using an improved technique to label bacteria isotopically (Hart and Jarvis, 1993; Jarvis and Hart, 1993).

During 1971, Paul Skelton works on the osmoregulation of *Tilapia* with a scintillation counter and joins the Albany Museum after graduating. At the time, Brian Allanson said to him: "*Well, this is the end of your career as a scientist*"!

Peter Keulder undertakes C^{14} primary productivity experiments and radio-isotope studies as part of his primary research for his PhD on the hydrochemistry of the Orange River and tributaries near the Lesotho border. Johan Grobbelaar carries out continuous algal culture work. Peter Stegmann conducts his MSc studies on the water quality of Gariep Dam – focussing especially on suspended sediments, underwater light regimes and algal productivity, before moving on to do his PhD on the turbid waters of Wuras Dam.

AJH (Braam) Pieterse starts his work on the Vaal River from 1978, focussing on water quality issues at the Balkfontein flow-gauging weir where water was also abstracted for domestic use in nearby towns. He assesses the interrelationships between environmental variables and algal community structure (dominant species) in the Vaal River, evaluating the implications of algal species for water abstraction and water treatment processes.

Ken Tinley of the Natal Parks Board publishes a report on the fishing methods of the Thonga Tribe in north-eastern Zululand and southern Mozambique (Tinley, 1964). This report has a strong influence in the years that followed for the Pongolo Floodplain and management of flow releases from the Pongolapoort Dam to meet the needs of local people.

With the impending closure of the Pongolapoort Dam and concerns expressed by the Natal Parks Board for the impacts this would have for the Pongola River floodplain and Ndumu Game Reserve, the Committee for Inland Water Ecosystems (CWE) of the National Programme for Environmental Sciences launches a study of the Pongolo River floodplain in 1970. Chris Bornman and Jan Heeg are the driving forces at the University of Natal. The intention is to provide a scientific basis for allocating flow releases to sustain the floodplain. After preliminary surveys by Mike Coke (Natal Parks Board) and Paul Colvin and Charles Musil (University of Natal) a research programme conceptualised by Charles Breen and Jan Heeg (and later Stephen Blaber) around the concept of ecosystem trophic dynamics, is initiated in 1973. It sought to understand how the floodplain ecosystem responds to variation in river flow. Although a research station is established at Jozini, by today's standards working conditions were primitive. The only communication with the rest of the country is via a manually-operated, shared telephone service – no computers, e-mails, mobile phones, air conditioners, etc. Much of the work is conducted from tents set up adjacent to the pans.

On moonlight nights the team would listen to hippo snorting, pelicans herding fish and the whistling white-faced duck. The research of Hilton Furness, Hennie Kok, Kevin Rogers, Charles Walley and Alistair Buchan, Fiona Rogers, Terry Everson, Jill Slinger and Annelise Drewes elucidate system composition, structure and functioning and how these respond to flow. It also establishes the essential role of the floodplain in the lives of local people. The finding of a comparative analysis of costs and benefits of allocating water for sustaining floodplain processes and for allocating the same amount of water for irrigation suggests greater benefit when water was allocated to sustain the floodplain processes. This provides the basis of recommendations for managing river flows downstream of the dam. As the research programme progressed and the importance of the floodplain in the lives of local people became more evident, it is clear that the programme would benefit by connecting with researchers from the social sciences and John Torres joined some of the field trips. The notion of bringing social scientists into the fold was not viewed favourably by the CWE. This was somewhat ironic given that we were operating under the banner of 'Cooperative Scientific Programmes'. This irony was testimony to the gulfs that existed between research disciplines at the time and to the prejudices among those trained in the so-called 'hard' sciences. After the close of the Pongolo Research Programme some social research was conducted by Peter Derman and Clive Poultney but the key opportunity for transdisciplinarity had been lost.

None of the recommendations made by Heeg and Breen (1979) or Alexander (1982) are taken up and structured into policy and operating rules for the Pongolapoort Dam. Charl Bruwer establishes 'water committees' amongst communities on the floodplain to negotiate releases (Bruwer, *et al.*, 1996). However, over thirty years (2010) after the original work by Heeg and Breen (1979) and Alexander (1982) the requirements for the environmental flows (the Ecological and Basic Human Needs components of the Reserve) have yet to become formally incorporated into the operating rules for the Pongolapoort Dam.

As the Pongolo River floodplain research programme draws to a close Jan Heeg and Charles Breen direct their attention to a study of nutrient dynamics in Midmar Dam. At the time there is global interest in the role of nutrients particularly nitrogen and phosphorus, in limiting rates of algal production. Hilton Furness had earlier demonstrated the potential importance of phosphorus being bound in the acidic soils of the catchment. This stimulates interest in nutrient exchange processes between sediments and the overlying water. Among the other techniques that were used, were large 'isolation tubes' five metres in diameter, embedded in the sediment, that allow enrichment experiments to be carried out on columns of water isolated from the rest of the water in the dam. Allan Twinch, John Akhurst and Danny Walmsley are the principal researchers in this programme.

Piet le Roux, Director of Nature Conservation, Free State Provincial Administration, appoints two Scientific Officers to start fish research in the Free State province.

Kobus Eloff, Amie van der Westhuizen and Gert Krüger start the *Microcystis* work at the Department of Botany, University of the Orange Free State in 1973. Kobus becomes Head of the Department of Botany in 1973 and Van Zinderen Bakker forms the new Institute for Environmental Sciences (IES). A major research focus is on limnology and toxic algae (cyanobacteria). At this stage limnology is taught at the 3rd year level and a new limnology honours course is established, with the departments of Zoology, Microbiology and Geology, and the Institute for Groundwater Studies participating in the course.

From the late 1950s, aquatic science research focuses mainly on important river and reservoir systems that provide water supplies to urban, industrial and agricultural users in the then Transvaal and Natal provinces of South Africa. This is complemented by the detailed taxonomic research on diatoms as indicators of water quality and toxicology that are conducted by Dr B.J. Cholnoky and subsequently by Drs F.R. Schoeman and R.E.M. (Archie) Archibald. This diatom research forms the basis for rapidly expanding research on the ecology and management of blue-green algae, particularly the toxic forms of *Microcystis aeruginosa* that are becoming increasing responsible for adverse water quality problems and human health risks in water supply reservoirs across the country.

Tony Ribbink and his team carry out detailed studies over several years on the taxonomy and ecology of many of the cichlid fish species in Lake Malawi (Ribbink *et al*., 1983).

The Natal Town and Regional Planning Commission are very influential in Natal in 1960s and 1970s and provide vision, drive and funding for freshwater work. Reports are published as blue Town and Regional Planning Reports. They also publish two seminal works by George Begg on the Estuaries of Natal and the Wetlands of Natal.

In 1974 Paul Roberts of the Department of Water Affairs starts to ask important questions about how much water should be kept in rivers, but mostly for supply to tourist camps and for animal (both livestock and wildlife) drinking. He later develops the first estimates of the quantity of water that is needed to sustain functioning river ecosystems (Roberts, 1981; 1983). Paul subsequently applies his thinking to South African estuaries, stimulating the first studies to estimate the water quantity and water quality requirements of estuaries as a basis for their effective management.

Several aquatic science researchers at the South African Medical Research Council, Potchefstroom University and the University of Natal working on snail ecology make important contributions to our understanding of the water-related disease bilharzia. Other researchers working on pest species of *Simulium* broaden our knowledge of the veterinary implications of *Simulium* outbreaks to stock farmers.

THE PIPES, THE PIPES ARE CALLING!
by Maitland Seaman

Over some short winter days and very dark and icy-cold nights in July 1978, four of us from the Limnology Division of the NIWR carried out a 48-hour study on stratification on Buffelspoort Dam on the north side of the Magaliesberg, about half way between Hartbeespoort Dam and Rustenburg. Dan Walmsley and I were studying the Dam, and needed there to be no moon to affect plankton migration. Colleague Roy Wilkinson and Dan's student assistant and brother-in-law Pete Vorster came along to help us, and possibly to enjoy a bit of adventure. We had the big 5.5 metre catamaran "Flos-aquae" moored out in the deepest part of the lake, some few hundred metres from the dam wall, whose crest was not visible because it was overflowing fairly strongly – who knows how strongly, 20, 30, 40 cm, it didn't concern us too much, then. A few years before, I had custom-designed the boat to have a large flat open deck plus a sampling hatch amidships near the back. It also had a canvas-covered frame to keep the sun off us. So it was a nice stable boat for sampling. Dan and I in particular had had some great fun and many escapades on it, but none compared with what happened that first dark and miserable night on Buffelspoort Dam. We had hired a caravan to sleep in, and left our warm beds in turns to go out to sample the icy waters every few hours. Pete Vorster and I were on the 2 am shift. There was a gale blowing down the valley, as often seems to happen at that ungodly hour in winter. We took the dinghy out to the big boat, tethered it to the stern by what turned out to be a flimsy bit of nylon cord and started sampling – sending down the standard probes, taking water samples at a range of depths for algal and chemical analysis and letting out 25m of very robust reinforced yellow 65mm plastic pipes for sampling zooplankton at a range of depths. We'd got as far as letting the pipes out and noticed that though the big boat was anchored fore and aft, it had begun to slip anchor. The canvas "roof" acted as a very effective sail. First the stern anchor slipped, then the prow anchor, then ever more rapidly one after the other. At first we weren't worried; we were far from the overflowing wall. So, what to do. We stayed calm (at two o'clock in the morning, in the middle of a dam, with not a soul awake or aware of us for miles around), we had to move to shallower safer waters. We had no time to pull in the pipes because we were by now moving at speed, driven by the wind and the wind-induced current, and the general river flow toward the overflowing dam wall. We had to move quickly. So I started the engines (luckily they took), we pulled up the stern anchor and Pete was pulling up the prow anchor when things started getting complicated. The pipes were still out, too bad, but then the strength of the wind snapped the tether of the dinghy which then started rapidly overtaking us. Still no panic, Pete would hold the anchor as well as he could and I would manoeuvre the big boat to "capture" the dinghy like a tugboat, with the big boat's square prow. Which happened, I must say, but by this time we were perilously close to the overflowing wall, under the baleful security floodlights, so much so that I looked down over the wall at the river 30 metres below us. We were young and surely believed in our own immortality, but we could so easily have flowed over the wall with that rushing water, to certain deaths. When got to shore with souls intact, but with the pipes broken off from the pump, our only loss, we'd perhaps foolishly saved both boats, and coincidentally risked our lives. Understandably, Dan knows the "Londonderry Air", otherwise known as "Danny Boy", which goes "... the pipes, the pipes are calling...", and they still are, as they lie for posterity in the soft sediment of the deepest part of Buffelspoort Dam.

The Department of Water Affairs and Forestry takes a decision in 1978 to limit the allowable maximum concentration of phosphorus in treated effluent to one milligramme per litre, where the effluent is intended for discharge into a designated "sensitive" catchment. This limit is incorporated into the Special Effluent Standard for sensitive catchments and is intended to minimize the risks of eutrophication in water storage reservoirs. The decision is taken despite clear and unequivocal evidence that effluent phosphorus concentrations need to be far lower, preferably no higher than 0.1 milligramme per litre. In addition, the decision to implement the one milligramme per litre effluent phosphorus standard has at least one unintended consequence in that it stalls a large body of research conducted by Dr James Barnard and his NIWR team who developed the Bardenpho (BARnard DENitrification and PHOsphorus removal) technology to remove phosphorus (and nitrogen) from domestic effluents. James Barnard eventually moves to North America where his Bardenpho process is received with acclaim. Several variants of the Bardenpho process are now used in virtually every wastewater treatment works in North America. Ironically, South Africa is apparently considering importing this technology for local use. A missed opportunity indeed!

3.3 Institutional landscape

Schonland believed that support for university research should receive priority attention, and made this responsibility one of the six core functions of the CSIR. He warns against a trend of researchers moving from basic research to more applied industrial research, believing that universities might lose 'the great teachers and scholars of the future', and that if such a trend were to continue, applied research and technology would dry up having used up the intellectual capital provided by the scholars. He believes in supporting university scholarship and research sufficiently to ensure that careers in university research would attract first class brains (Kingwill, 1990).

Schonland devises a scheme for Consolidated University Research Grants, providing for a range of bursaries as well as grants for running expenses. Universities would screen and submit all their applications to CSIR and after review each university would receive a consolidated grant for all approved applications of which they had to administer the individual awards. In 1946, the CSIR starts its university research grants section with a total budget of £27,800 but receives applications amounting to only £16,526 (Kingwill, 1990). In the same year, a Research Fellowship in Ichthyology (£800 per annum for three years) is awarded to J.L.B. Smith (Pote, 1996). Mark Chutter recalls that for field trips in the late 1940s, he applied for a car and a chauffeur. A gallon of petrol cost one shilling and four pence (about 14 cents) and a pH meter was a huge box with a control electrode.

Before 1952, only departments of inland fisheries existed, with a particular focus on sport angling. After 1952 these departments are transformed to departments of nature conservation that absorb the fisheries activities. The Jonkershoek Nature Conservation Unit (part of the then Cape Provincial Administration) and the Lydenburg Fisheries Research Unit (part of the old Transvaal Provincial Administration), carry out important surveys on the identity and distribution of indigenous fish species as well as breeding and distributing trout fingerlings to farmers and anglers. A lot of work is conducted in the different South African Museums (Cape Town, Bloemfontein, Albany, Natal, Pretoria), though the studies carried out by museums tended to focus on specific taxa of interest to their scientists. Between 1950 and 1980, each of the nature conservation departments in South Africa's four provincial administrations support a fisheries station where research is carried out on native fish species, while trout (and later bass) are bred for distribution to farmers and anglers.

Prior to the introduction of the Water Act of 1956, South Africa's national policy in the water field focuses on supplying water to agriculture, mines, industry and urban centres.

During the 1960s, the CSIR establishes a number of Research Units at South African universities. These Research Units are mostly built up around established researchers with outstanding records of achievement. One of these units with particular relevance to aquatic science is the Palynology Research Unit at the University of the Orange Free State, which is headed by Van Zinderen Bakker.

During the 1963 annual meeting of the South African Association for Advancement of Science (also known as S_2A_3), Mark Chutter, Graham Noble and Brian Allanson thought that this association had little to offer those who specialised in limnology. They walked out of the conference, met in a pub across the street, and decide that it was time to start a new society that would serve the interest of limnologists. They also decide that Arthur Harrison (who was a good friend of the three but absent during their discussions) should be the first president of the new society. That is how the Limnological Society of Southern Africa (LSSA) was founded, in 1963 in Grahamstown.

During the 1960s and 1970s, significant research on the freshwater systems of Natal (now KwaZulu-Natal) is conducted under the aegis of the Natal Town and Regional Planning Commission (now the KZN Planning and Development Commission (KZNPDC)). The Commission adopted the policy that it should have accurate and authoritative records of the natural resources in Natal, and therefore embarks on a fairly comprehensive research programme, partnering with well-known researchers to ensure that the information was gathered and published. In an approach to promote the integrated use and conservation of natural resources, the commission supports research ranging from conservation to catchment management to disposal of effluents.

During the late-1960s and into the 1970s, staff members from the NIWR's Durban office carry out extensive studies on the coastal lakes of northern Natal (*e.g.* lakes Cubhu and Msingazi) and the recently dredged harbour at Richards Bay. The Richards Bay team uses a small hovercraft – the first scientific use of such a vehicle in South Africa – to collect samples from sites located in areas that were inaccessible by a conventional boat with an outboard motor. On one occasion, a mechanical failure in the hovercraft strands the NIWR crew on the exposed mudflats, with a rapidly rising tide, some kilometres from the shore. This requires everyone to wade to shore through thick, glutinous mud, carrying equipment and samples, mindful that there had been numerous sightings of large Bull sharks in the harbour area!

Pete Ashton recalls the 'dress code' for men at Rhodes University in 1967, when men students were required to wear a jacket and tie to all lectures. When he attended a second-year zoology lecture delivered by Professor Brian Allanson, without the requisite tie, Brian Allanson said "*Sir, you are incorrectly dressed. Remove yourself*". Pete 'removed himself' as instructed but decided that he would prefer to visit the local 'watering hole' rather than return to the lecture. When asked at a subsequent lecture as to why he had not returned 'properly dressed', the explanation as to having been 'waylaid by an overwhelming thirst' did not go down well with Brian Allanson. At UCT the dress code was relaxed for lectures, but men had to wear a tie and women a skirt if visiting the Registrar's office! Richard Robarts' arrival in 1970 from Canada with long hair and a beard, and dressed in a T-shirt and blue jeans changed the tone of the Zoology Department at Rhodes. Following his departure in 1973 to Zimbabwe Brian Allanson explains to staff and students that there would be no more 'Christ-like' figures in his department! Rand Afrikaans University has a similar dress code and Hendrik Schoonbee is also remembered for requesting a number of students without a tie to leave the lecture hall.

Mike Coke recalls that, between 1967 and 1973, he did fieldwork on the Pongola floodplains for 10 days at a time, once every month, at will. Lengthy field trips of this nature were the norm at the time.

Both Mike Coke and Peter Ashton went on to be editors of the *South African Journal of Aquatic Science*, now the *African Journal of Aquatic Sciences.*

Jim Cambray remembers that the Cape Nature Conservation fish research team was joined by the Albany Museum team of Paul Skelton and Cecil Nonqane on a collecting trip along the Orange River in the 1970s. At one location the team was using one of those dangerous homemade electro-fishers – a generator on the shore with long electric cables with a cheap on/off switch on the anode. The team always, well mostly, made sure that someone was at the generator to switch it off if the person with the anode was in trouble. One day, Jim was electro-fishing in the rapids for catfish and Paul Skelton was at the generator. Jim had run out of cable so Paul was helpful and brought the generator closer. Unfortunately this was not along the shore but into the water. Well that was the end of the generator but the waderless Paul Skelton survived and the results were published (Skelton and Cambray 1981).

South Africa belonged to International Council for Scientific Unions (ICSU), which was founded in 1931 as an international non-governmental organization devoted to international co-operation in the advancement of science. Although South Africa was a member of this international organisation from 1931, its first active participation in an ICSU activity was in planning for the International Geophysical Year (1957-1958). The successful participation of many South African scientists in this international event creates a platform for further international cooperation in research. A series of international scientific programmes is launched by the ICSU with increasing involvement by South African scientists. Of note was the International Biological Program (IBP), an ICSU effort between 1964 and 1974 to coordinate large-scale ecological and environmental studies. South African scientists respond readily to this cooperative research opportunity, focussing on the productivity of terrestrial, freshwater and marine communities, conservation, use and management of biological resources, and human adaptability. The participation of South African researchers in this work is influential to the future direction of, and support for, environmental research in the country.

The success of South African participation in the ICSU programmes leads to the establishment of a number of national Co-operative Scientific Programmes. One of these is the National Programme of Environmental Sciences, established in 1972, with sub-programmes for inland water ecosystems, terrestrial ecosystems, marine pollution, the atmosphere, waste management and human needs. Research on inland water ecosystems includes mineralization, aquatic weeds, eutrophication, coastal lakes, manmade lakes, the Pongola floodplain, cattle-biting flies and heavy metals. The ecological components of the National Programme of Environmental Sciences are later grouped together and renamed the National Programme for Ecosystem Research. This programme provides the space for multi- and interdisciplinary research on complex environmental problems.

Soon after the International Biological Program ends in 1974, the CSIR forms the Cooperative Scientific Programmes (CSP) in 1975 as a unit within CSIR, with Dr R.G. Noble as its first Director. The purpose of CSP is to coordinate all the national cooperative scientific programmes. By 1980, active cooperative scientific programmes exist in the fields of Antarctic, earth, marine, atmospheric, space, environmental, materials, and energy research. The CSPs are the envy of many parts of the world – many overseas researchers express considerable surprise that a research community, which is small enough for everyone to know each other, could do such significant work.

In 1979, the SIL Workshop on African Limnology is held in Nairobi, Kenya. Because of the prevailing political isolation, the conference organizers are pressured by outside interests to prevent the participation of South African limnologists. However, South Africa’s strong ties through the International Council of Scientific Unions (ICSU) enable this situation to be bypassed. As a compromise, the conference organizers indicate that only a limited number (10-12) of South African passport holders would be allowed to participate in the conference. In the end, about 45 members of the South African limnological community arrive at the conference, having travelled there on a variety of foreign passports. The social and technical interactions between limnologists based in South Africa with their counterparts from other African and overseas countries build strong ties of professional collaboration.

Up until about 1980, the primary source of research grants for aquatic scientists is from CSIR. These research grants are normally only provided to established / senior researchers and professors at universities. These scientists have almost complete freedom to choose their research topics but never receive truly significant amounts of backing in terms of the funding they received. Most researchers are unable to afford the cost of new (imported) equipment so they make their own field equipment and work on issues that they are interested in.

4 THE TURBULENT TRANSITIONAL YEARS (1980-1994)

4.1 Chronology of key events

1980 – Dr C.F. Garbers is appointed President of CSIR and immediately faces significant challenges brought about by changing external circumstances and shrinking sources of funding.

1980 – Rhodes University initiates a Masters Degree in Limnology, following the endowment of a Chair in Postgraduate Limnology by the then Barclays National Bank (now First National Bank). This chair will be held for its duration of 5 years by Rob Hart. The MSc is structured as a combined course-work and mini-thesis programme, which roughly 12 students will complete. The first two students were Dave Taylor and Mike Silberbauer.

1980 – Ronald Reagan becomes the 40th President of the United States and maintains relatively cordial relations with the then Apartheid South African government.

1980 – The J.L.B. Smith Institute for Ichthyology is declared a Cultural Institution, to be funded by the Department of National Education.

1980 – The South African Institute for Medical Research, the South African Medical Research Council and the Johannesburg Department of Health produce an important joint publication *Atlas of Bilharzia in South Africa* (Gear *et al*., 1982).

1980 – Publication of *Studies on the Ecology of Maputaland*, edited by M. N. Bruton and Keith Cooper (Bruton and Cooper, 1980).

1980 – Start of the Hartbeespoort Dam Ecosystem Program headed by Mark Chutter at the Limnology Division of the NIWR at CSIR. This research programme continues for several years and produces definitive information on the nutrient cycling and the ecological functioning of this hypertrophic water storage reservoir (NIWR, 1985).

1980 – The Department of Water Affairs introduces a policy to include predictions of environmental impacts when planning new bulk water infrastructure projects. However, these investigations only focus on predictions of what were considered to be ‘relevant’ impacts (no-one seems to be quite sure about to whom or to what the impacts would be ‘relevant’). Therefore, while this was a welcome development, it falls well short of common environmental impact assessment practice.

1981 – The first IBM Personal Computers enter the market.

1981 – The Riviersonderend-Berg River-Jonkershoek Project to augment water supply to the Cape Town municipality and surrounds is completed.

1982 – The report on *Man and the Pongolo Floodplain*, (Heeg and Breen, 1982) is published by the National Programme for Environmental Sciences, CSIR, demonstrating ways of linking ecological and social issues.

1983 – Start of a National Programme for Aquaculture Research.

1983 – The University of the Free State starts an Honours Degree in Limnology under Braam Pieterse and Johan Grobbelaar.

1984 – Dr D.F. Toerien succeeds Dr G.G. Cillié as Director of the NIWR at CSIR.

1984 – The Southern Hemisphere Limnology Conference and workshop are held at the Wilderness. This is a testament to the scientific credibility that aquatic science had achieved under the Cooperative Scientific Programmes. The proceedings of this conference are edited by Bryan Davies and Danny Walmsley (Davies and Walmsley, 1985)

1984 – The amalgamation of the CSIR's Research Grants Division and the Co-operative Scientific Programmes give birth to the CSIR's Foundation for Research Development. This operates as a separate entity within CSIR. The FRD will later (early 1990s) abandon the programmatic approach to environmental research.

1984 – Initiation of the Freshwater Research Unit at the University of Cape Town by Bryan Davies, Jenny Day and Jackie King.

1985 – Dr Glenn Merron of the J.L.B. Smith Institute for Ichthyology leads the establishment of a research station in the Okavango Delta near the town of Maun (Botswana) with funding from the WWF, the Southern African Nature Foundation and the Kalahari Conservation Society.

1985 – The White Paper on Industrial Development Strategy in the Republic of South Africa poses a new set of challenges to the CSIR, particularly related to the transfer of technology to the public and private sectors (Kingwill, 1990). This leads to a new era for the CSIR, with ramifications affecting scientific research in the rest of the country.

1985 – Publication of the National Scientific Programmes' report *The Limnology of Hartbeespoort Dam* – the first multi-authored report coming out of the Hartbeespoort Dam Ecosystem Programme program.

1986 – Publication of first textbook on wetland ecology (Mitsch and Gosselink, 1986).

1986 – The Natal Town and Regional Planning Commission publishes the first part of a series on the Wetlands of Natal by George Begg (Begg, 1986). This leads to widespread appreciation for the importance of wetlands in landscapes.

1986 – Publication of the 'Red Book' on *Management of the Water Resources of the Republic of South Africa* (DWA, 1986), compiled and edited by Allan Conley, with contributions from several scientists and engineers in the department.

1986 – Cape Department of Nature Conservation removes legislation for the protection of trout, a milestone for the conservation of endangered indigenous freshwater fish species in the Cape.

1986 – DWA declares its intent to allocate water to sustain the natural environment. An invitation to be exposed to the state of rivers flowing through the Kruger National Park culminated in 'The Kruger rivers trip', which provides a key stimulus for improving the relationships between aquatic scientists and engineers responsible for water resources planning and management. This leads to DWA convening a workshop in 1987, followed by the initiation of the Kruger Park Rivers Research Programme (KNPRRP) in 1988 as a joint venture between Department of Water Affairs, the Department of Environment Affairs, the WRC and the FRD. The KNPRRP introduces the concept of adaptive management.

1986 – Tony Ferrar of FRD arranges an important workshop on the impacts of flow-modifying structures on river ecosystems and on ecological water requirements for South African rivers and the impacts of flow-modifying structures (Ferrar, 1989). The discussions at this workshop pave the way for the development and testing of improved approaches to define the ecological flow requirements of rivers and the operating rules for water storage reservoirs. These approaches later become incorporated into methods to estimate the size (volume, timing and duration) of flows for the ecological component of the Reserve.

1986 – The Institute for Environmental Sciences at UOFS is replaced by the Unit for Limnology.

1987 – The Palmiet Pumped Storage Scheme is completed. The project is hailed for its environmental protection plan, which requires special construction methods.

1987 – Phase 1a of the Lesotho Highlands Water Project, including the construction of Katse Dam, is completed. Water flows from Katse Dam via a tunnel through the Maluti Mountains and under the Caledon River to South Africa. The project is criticised in international circles for receiving the go ahead without any environmental impact assessment being carried out. Some 35 baseline studies of the area's flora and fauna are only undertaken several years after the construction of Phase 1a began.

1988 – CSIR's President Brian Clark delivers his so-called "sermon on the mount", which announces impending changes in CSIR's mission and financial operating model to one focussed on 'contract research'. This new business model signals an abrupt change in the way that CSIR would undertake research, with much greater attention being paid to 'confidential' and 'commercial in confidence' contracts. The obvious down-side to this is that many CSIR scientists are encouraged not to publish their results in the peer-reviewed scientific literature because this would be 'giving away' their knowledge and insights. The unanticipated impact of this new operating model is that the careers of many CSIR scientists suffer because external perceptions of their scientific ability are based on dwindling numbers of high quality publications.

1989 – Mikhail Gorbachev and George H. W. Bush declare the Cold War over at the Malta Summit.

1989 – Professor Bill Williams from the University of Adelaide in Australia is commissioned by the then Foundation for Research Development (now National Research Foundation) to assess the status of limnology in South Africa. The resulting report (Williams, 1989) remains strictly confidential until the National Research Foundation agrees to release the report to Peter Ashton and Dirk Roux in 2010 for use in this study.

1990 – Publication of *Inland Waters of Southern Africa: An Ecological Perspective* – this is the first textbook on South African aquatic systems (Allanson *et al.*, 1990). Surprisingly, this book contains no mention of any of the features of or studies on the Vaal River, arguably one of South Africa's most important rivers.

1990 – Nelson Mandela is released from jail.

1991 – Tim Berners-Lee creates the World Wide Web.

1991 – Publication of *Water Quality Management Policies and Strategies in the RSA* by the Department of Water Affairs (DWA, 1989).

1991 – The Institute for Water Research is established by Rhodes University by merging the Institute for Freshwater Studies and the Hydrological Research Unit. Denis Hughes and Jay O'Keeffe alternate as Director.

1992 – The Rio Summit takes place in Rio de Janeiro, Brazil.

1993 – Publication of *Freshwater Fishes of Southern Africa* (Skelton, 1993). This is followed a few years later by a revised version *A Complete Guide to the Freshwater Fishes of Southern Africa* (Skelton, 2001).

1994 – The first national election under universal adult franchise is held in South Africa.

1994 – New provincial boundaries are drawn up, segmenting South Africa into nine provinces.

1994 – The Hydrological Research Institute is renamed as the Institute for Water Quality Studies with Dr H.R. van Vliet as the Director.

1994 – A joint South African / Australian workshop on the classification of rivers and river health indicators is held in Cape Town (Uys, 1994).

1994 – Netscape is launched.

1994 – Publication of *Surface Water Resources of South Africa 1990*, by the Water Research Commission (Midgley *et al.*, 1994).

1994 – A Centre for Environmental Studies, and a new degree, Master of Environmental Management, is established at the University of the Orange Free State.

4.2 Individuals and topics of note

During the 1980s, the Cape Provincial Department of Nature Conservation (now called Cape Nature) initiate monitoring of fish populations in the Orange River and its two major impoundments and this monitoring continues for at least 20 years. Kas Hamman completes his PhD on the responses of post-impoundment fish populations in the Gariep Dam and some impacts of the large impoundments in the Orange River on certain fish populations. Jim Cambray and Ben Benade are also prominent in this type of work (*e.g.* Cambray *et al.*, 1997; Cambray, 2003). During this period, Kas Hamman is instrumental in removing protection for alien fish species from CapeNature Ordinance. The focus changes from managing rivers for the maintenance of alien fish species to managing for native species. Jonkershoek stop rearing alien fish. There is now a significant research focus on culture (*e.g.* whitefish – Mr T Smith; Clanwilliam yellowfish – Dr Anton Bok) and the habitat requirements (Clanwilliam yellowfish, Breede redfin) of Western Cape fishes.

During the 1980s, Dawid Coetzee conducts detailed scientific studies on estuarine ecosystems in the southern Cape, specifically Swartvlei. During the same period, Thomas Ratte conducts detailed scientific studies on Groenvlei in southern Cape, and one of first intensive genetic studies on estuarine fishes in RSA, focusing on *Atherina* and *Gilchristella*.

During the process of revising South Africa's Water Law, SASAqS organizes provincial meetings to compile the inputs of members and nominate Tally Palmer as their representative to serve on the Ministerial Advisory Panel tasked with revising South Africa's water law. The deliberations of this Panel produce a set of key principles and the White Paper that forms the basis of the Water Act (Act No. 36 of 1998).

Ferdy de Moor completes a PhD on *A community of Simulium species in the Vaal River near Warrenton* (De Moor, 1982). This follows on from the earlier studies by Mark Chutter and he devises an integrated flow regulation programme using flow cessation and natural predators of blackflies to control and reduce the population size of the pest species *Simulium chutteri* (De Moor and Chutter, 1979; De Moor, 1982; 1992a; 1992b).

The Research Unit for Fish Biology with Hendrik Schoonbee as Director starts in the Department of Zoology at RAU in 1980 and is changed to the Research Unit for Aquatic and Terrestrial Ecosystems in 1990, with Hein du Preez as Director. The unit is dissolved in 1997 as a result of policy changes at the university. During the mid-1980s and early 1990s the research focus shifts to aspects related to aquaculture and Hendrik Schoonbee starts work on bioaccumulation in wetlands, concentrating on the accumulation of metal ions in fish. However, because of the decline in interest and slow developments in aquaculture, the department is forced to refocus its research. New research programmes are initiated in two focus areas, namely aquatic ecotoxicology and biodiversity and conservation, which include previous research interests such as fish physiology, bioaccumulation of metals, fish parasitology and population genetics.

The first studies on receiving water quality objectives are carried out by an NIWR research team – accompanied by specialists from DWAF – working on the SASOL effluents that were being discharged to the Vaal River. This work expanded the concepts of so-called 'assimilative capacity' for use in estimating the ability of streams and rivers to tolerate specific water quality constituents. Later studies continue these applications on the Crocodile (East) River and the Ga-Selati River. However, further work also revealed that most of the so-called 'assimilation' that took place was merely dilution and that the total load of water quality constituents remained virtually constant.

The foundation of UCT's Freshwater Research Unit in 1984 catalyzes the Western Cape as an important centre of freshwater research. Interest in rivers had been revived with the publication of data from Jackie King's PhD studies on the Eerste River. A little later in the 1980s Jackie King, Bryan Davies and Jenny Day study two small tributaries of the Eerste River streams in the Jonkershoek Valley; and Delny Britton conducts her PhD research on the effects of a controlled burn on a third tributary. At much the same time Barbara Byren Gale studies the highly regulated Palmiet River for her PhD. Tony Gardiner's PhD thesis is the first work on local wetlands for more than 20 years. All of these studies are funded by the CSIR's Fynbos Biome Programme. Towards the end of the 1980s Jackie King and Mike Silberbauer carry out an extensive survey of wetlands of the south-western Cape, funded by the Cooperative Scientific Programme's Wetlands Programme. The CSP is disbanded in the middle of this programme and the work is never completed.

Ecological studies on temporary waters – especially pans – start at the University of the Free State in the late 1980s and still continue today (Seaman *et al*., 1991). This research is led by Maitland Seaman, and produces a number of PhD students. Jenny Day at UCT also undertakes studies on temporary pools in the Namib Desert of Namibia.

Dawie Botes and his colleagues from the CSIR's National Chemical Research Institute are the first to describe the chemical structure of cyanoginosin-LA – now called microcystin – the toxin produced by the cyanobacterium *Microcystis* (Botes *et al.*, 1984). The latter is the main scum-forming species in many South African reservoirs including Hartbeespoort Dam, where it reaches massive proportions (scums were greater than 1 metre in depth), which are later called 'hyperscums' (Zohary, 1985).

Earlier research on the causes and consequences of nutrient enrichment (eutrophication) and sediment transport lead to the commissioning of detailed limnological studies of water supply reservoirs throughout South Africa (Walmsley and Butty, 1980). At the same time, there is some international collaborative work on invasive aquatic plants such as water hyacinth (*Eichhornia crassipes*) and red water fern (*Azolla filiculoides*) (Ashton, 1982; Ashton and Mitchell, 1989). The NIWR undertakes detailed limnological studies that provide a firm basis for the first successful chemical control programme against water hyacinth at Hartbeespoort Dam (Scott *et al*., 1979). The subsequent replacement of water hyacinth with a large *Microcystis* bloom, coupled with the decision by DWAF to implement a 1 mg/litre phosphorus upper limit as a key part of the Special Effluent Standard, prompt the start of the multi-disciplinary Hartbeespoort Dam Ecosystem Program in 1980, which focuses on the cycling of phosphorus. This ecosystem programme, headed by Mark Chutter and Richard Robarts, continues until 1989. It is designed around a routine monitoring program, and proves to be an example of the scientific benefits coming out of a multi-disciplinary team of researchers, all studying the same ecosystem. The programme brought into light the ultimate fate of lakes that undergo severe eutrophication, culminating in massive 'hyperscums' of toxic cyanobacteria. Hartbeespoort Dam is probably the most hypertrophic lake studied intensively anywhere in the world at that time. The results of the eutrophication research coming out of the program evoke considerable interest worldwide, far beyond the boundaries of South Africa. A detailed report on the physics, chemistry and ecology of this important water supply reservoir (NIWR, 1985), is followed by more than 80 scientific publications in peer-reviewed journals, as well as four PhD theses (Kevern Cochrane, Andrew Jarvis, Tamar Zohary, John Hely-Hutchinson), all based on the Hartbeespoort Dam Ecosystem Programme (Zohary *et al.*, 1988).

The scientists on the Hartbeespoort Dam team are: Mark Chutter (director), Richard Robarts (advisor to director; primary productivity, microbial ecology with Richard Wicks), Peter Ashton (nitrogen and phosphorus transformations and nutrient modelling), Allan Twinch (phosphorus and sediments), Willem Scott (*Microcystis* toxicity), Jeff Thornton (eutrophication management), Andrew Jarvis (zooplankton), Tamar Zohary (phytoplankton, focus on *Microcystis*), Kevern Cochrane (fish populations, ecosystem modelling), Ferdy de Moor (fish feeding), John Hely Hutchinson (lake physics) (NIWR, 1985).

The mid-1980s also see the start of detailed ecological studies on key river systems such as the Vaal and Crocodile (East) rivers, including investigations on nutrient dynamics, ecosystem structure and function, and the influence of a variety of pesticides and agro-chemicals. Initial estimates are conducted on the potential influence of climate change on the water quality characteristics of selected river systems.

Remote sensing under Alison Howman at HRI initially uses a card reader for input and a line printer for output, colouring in the blocks with felt pens. This was followed by use of the CSIR's Satellite Application Centre equipment and eventually, in 1985, a stand-alone mini-computer is installed at HRI. Political sanctions at the time complicate the purchase of this instrument. Several of the first remote sensing specialists at HRI were conscientious objectors who are doing six years of compulsory non-military public service in lieu of military service.

Water quality modelling is carried out by Dirk Grobler and Andrew Bath at HRI, and Andre Görgens at NIWR. These studies led to a wider appreciation of the need to model the fate and transport of water quality constituents in rivers and reservoirs. The Hartbeespoort Dam research team develop the TROFIC model to simulate the movement of phosphorus through all biotic and abiotic compartments in the reservoir (Clark *et al*., 1987; Cochrane *et al.*, 1987). Much later, modelling work on coastal lakes is conducted by Bill Harding at Southern Waters, later at DH Environmental Consulting, and leads to the development of the NEAP software (Rossouw *et al.*, 2008) which is now used to assess South African reservoirs (Harding, 2008).

Tony Ferrar at FRD directs the South African National Scientific Programme on the ecological water requirements of river systems from 1986 to 1989. This programme culminates in an important FRD report (Ferrar, 1989) that lays the basis for many later studies on ecological flow requirements in rivers.

A new application of advances in aquatic science is initiated with the development of preliminary water quality guidelines for the rivers flowing through the Kruger National Park (Moore *et al*., 1991) and the start of various comprehensive whole-catchment water quality studies, for example, on the Crocodile (East) River basin in Mpumalanga (Heath *et al*., 1995), and the development of the first edition of water quality guidelines for aquatic ecosystems (DWAF, 1996b).

Bryan Davies completed his PhD, then a post-doc in 1974, going to Rhodes University, and then moving to UCT in 1980. In 1984 Bryan leads the drive to start the Freshwater Research Unit at UCT and becomes the unit's first director in 1984. Bryan Davies is articulate, passionate and outspoken, working on rivers in the south-western Cape, impoundments (Cahora Bassa), coastal lakes (Wilderness) and inter-basin water transfers (IBTs) and also manages a large FRD programme on rivers in the early 1990s. The South African limnological textbook *Vanishing Waters*, written by Bryan Davies and Jenny Day, arose as series of extra-mural lectures. The first, rather slender, edition appeared in 1987, and rapidly went out of print to be replaced by an updated and expanded second edition in 1998. Bryan is a very good lecturer and loved by his students.

Roland Schulze (UKZN) and Des Midgley (Wits) start hydrological modelling in South Africa, a trend that was mirrored by the development of a range of water quantity and water quality models elsewhere in the world. The increased availability of computing power provides an important stimulus for new efforts in water quality and hydrological modelling, especially by Dirk Grobler and Mike Silberbauer at HRI. Mainframe models evolved into PC models – Andrew Bath uses American and Australian hydrodynamic reservoir models for modelling phosphorus (especially in the Berg River). This leads to an increased awareness of the need for catchment-scale monitoring and, in particular, for synoptic monitoring at many sites within a catchment.

The national Department of Water Affairs (DWA, which later became the Department of Water Affairs and Forestry – DWAF, and in 2010 once again became the Department of Water Affairs – DWA) is responsible for an intensive programme of dam building throughout the country. These water storage dams are built to supply water for irrigation use and to supply water to urban areas. Because many of these dams are located downstream of urban and industrial areas, their inflows contain increasing quantities of treated, partially treated and untreated effluents as well as agricultural return flows and industrial effluents. This leads to an initially gradual – but now accelerating – increase in the degree of enrichment and contamination in these reservoirs. In turn, the water quality in the affected reservoirs becomes increasingly less fit for use and this leads to a steady increase in the costs of treating water to meet user requirements. On the positive side, these developments stimulate increased studies into in-lake processes and options to deploy in-lake remedial measures.

The national Department of Water Affairs uses inter-basin transfer schemes as an important means to provide sufficient water to those areas and segments of the economy where water supplies were scarce. These transfer schemes also prompt research into the possible negative effects of inter-basin transfers, with work being done on the Fish River by Mark Chutter before water transfer from the Orange River and by Jay O'Keeffe and Ferdy de Moor after water transfer starts. Bryan Davies leads a team of UCT researchers including Marcus Wishart and Kate Snaddon, who review the ecological implications of inter-basin water transfers.

In 1968 Mark Chutter predicts that the construction of impoundments and the resultant enrichment of the water released from these impoundments will favour filter-feeding larval Simuliidae (dipterans, the adult females of which are blood-suckers), causing them to become a problem species. Between 1977 and 1981 Ferdy de Moor undertakes research on the control of *Simulium chutteri* in the lower Vaal River, using short-term flow cessation at certain times of the year in conjunction with timing the life-cycle of natural aquatic predators such as hydropsychid Trichoptera to control the population size of this pest species. The findings of this research are published in a number of publications (*e.g.* Howell *et al.*, 1981) and also result in a PhD by Manfred Car from Onderstepoort. Ferdy de Moor undertakes the first field trials using a toxin produced by the bacterium, *Bacillus thuringiensis* var. *israelensis* (Bti), to specifically target blackfly for control in the Vaal and Orange Rivers between 1982 and 1984. Rob Palmer also undertakes research on the blackflies of the Buffalo River for his PhD and later (1995-1997) carries out research on the control of simuliids, mostly *Simulium chutteri,* using integrated control methods with Bti and organophosphates in the lower Orange River in the Northern Cape and Great Fish River in the Eastern Cape. Rob Palmer's work on *Simulium* populations in the lower Orange River also devises new methods for monitoring pest outbreaks of Simuliidae so that early control could be implemented.

The blackfly control programme on the lower Orange River illustrates the complex tensions that arise between the users of an aquatic resource, and suggests the scale of the problems that catchment management agencies will continue to face in future. At first, the Department of Agriculture and Onderstepoort manage the control programme nationally and provide a helicopter and chemicals as required. Rob Palmer, in his time at Upington, develops an effective monitoring programme and DWAF tries to embed this in the management structures that exist in the Orange River Valley.

After about a decade, the WRC withdraws its funding and a serious blackfly outbreak occurs because the monitoring-management cycle has not functioned properly and, for some unknown reason, the cheaper organo-phosphate larvicide has stopped working. Rob Palmer goes back in with renewed WRC support, though by this time his contacts at Onderstepoort and NDA had retired. For the control programme to effectively stop a spring outbreak, Eskom will have to stop generating hydropower at the Vanderkloof Dam for two weeks in mid-winter, the time of peak power demand. Eskom estimate that their cost in lost revenue would be about R2 million per day, and are reluctant to comply. The blackfly problem is costing the livestock industry of the lower Orange more than R30 million per year, and is causing additional losses in tourism and general human discomfort. Unfortunately, the parties do not reach any satisfactory conclusion to this negotiation.

4.3 Institutional landscape

4.3.1 Commercialisation of science

Worldwide, the advent of privatisation / commercialisation policies from the late 1970s and early 1980s mark the onset of a move towards de-nationalisation of research facilities while dwindling government funding pushes many establishments that previously relied upon government for funding to move into the market place to find resources elsewhere, often in partnership or in competition with others (Gibbons, 1999). These global policy changes are generally ascribed to the influence of Margaret Thatcher and Ronald Reagan – an influence that is today commonly referred to as 'Thatcherism' or 'Reaganism'.

Dr C.F. Garbers is appointed President of CSIR in 1980 and immediately faces significant challenges brought about by the changing external environment. These include persistent high rates of inflation, worldwide economic recession, the aftermath of the energy crisis of the mid-1970s, the weakening price of gold and the onset of severe drought across southern Africa (Kingwill, 1990). Further factors include an intensification of the South African Border War, intensified economic sanctions and disinvestment, civil unrest (especially between 1983 and 1986) and the social and political isolation brought about by enforced racial segregation policies (1948-1994). The South African Government has no choice but to curb expenditure and the CSIR and other research and academic institutions experience substantial budget cutbacks. This comes at a time when most of the developed technology-based countries are still investing heavily in science as a means of finding their way out of their own economic difficulties and of establishing their technological supremacy in the context of the Cold War (1945-1989). In response to budget cuts, CSIR decides against a policy of 'equal misery to all' and starts to selectively close down, phase out and transfer certain activities and units (Kingwill, 1990).

In 1988, CSIR's President Brian Clark delivers his so-called 'sermon on the mount' to the assembled staff members, which announces the impending change in CSIR's mission and financial operating model to one focussed on 'contract research'. The CSIR undergoes dramatic changes in its operations with the change from research focussed on issues of national strategic importance to contract research for individual clients. As a result of this change, technical reports on contract projects became far more important measures of 'scientific achievement' at CSIR than scientific publications in the peer-reviewed literature. This also marks a decline in the ability of many individual scientists to achieve international recognition for their research. Numerous scientists decide to leave the CSIR and in the process many left the country. This trend has continued ever since, with the total staff complement of the organization gradually declining from approximately 5,400 in 1980 to its current level around 2,100 – this despite a renewed focus on high quality scientific research.

To consolidate the administration of the funding schemes that CSIR made available to universities, the CSIR's Research Grants Division and the Co-operative Scientific Programmes amalgamate in 1984 to give birth to the CSIR's Foundation for Research Development. At that time, the Research Grants Division and the Co-operative Scientific Programmes administer research funds amounting to R10.5 million and R15 million, respectively. The Research Grants Division supports self-initiated research and centres of excellence that were built up around gifted individuals. In addition, the Co-operative Scientific Programmes unit supports co-operative studies to address complex national and international problems. The latter funds proposals based on the merit of the research workers as adjudged by a peer review system (Kingwill, 1990).

From being a central influence in almost all spheres of scientific research in South Africa between the late 1940s and 1970s, CSIR's new focus also changes its role and prominence within the scientific community. Jackie King recalls that "*from the late 1980s the CSIR stopped becoming an influence in our lives*". In part this was because aquatic researchers at the time started to access funds from the Water Research Commission. In fact, during the 1990s some academics develop a somewhat adversarial relationship with their counterparts at CSIR, primarily because they are now competing for the same scarce (and still dwindling) sources of funding. A common complaint at the time is that CSIR has an unfair advantage because of a perception that it still receives a government grant and uses that grant to increase its ability to secure other external funding.

The drive towards greater financial self-sufficiency and cost efficiency has a number of unintended consequences. One such consequence arises with the destruction of many of the project archives at the CSIR's Division of Water Technology. Many of the documents and files are pulped because of the high costs associated with curating enormous numbers of project files. This results in a considerable loss of technical information and potentially useful data sets, dramatically reducing the institutional memory these assets represent. Later scientists are not able to refer back to the results of earlier studies as a way to avoid unnecessary mistakes. An example is the limnological database coming out of the Hartbeespoort Dam Ecosystem Programme. The archive containing the physical, chemical and biological data generated by this programme during a whole decade, 1980-1989, is lost in the above manner. Miraculously, copies of some of the data are kept by Tamar Zohary who left CSIR and South Africa in 1989 and are returned to the NRF in 2010 for future storage. Recently, Richard Robarts (October 2010) provides copies of all his field and laboratory notebooks so that the physical, chemical and much of the biological data (primary production, chlorophyll *a*, bacterial production and numbers, etc.) for Hartbeespoort Dam from 1980 to 1988 can be recovered. In addition, a copy of the video of *Microcystis* in the reservoir made by Tamar Zohary and Richard Robarts is also provided – this video is still used in limnological courses in universities around the world to illustrate an extreme case of eutrophication.

The drive to achieve economies of scale and decrease operating costs ignores the fact that knowledge is located within individuals, is context specific, and cannot be replicated easily. The simultaneous focus on protecting so-called ‘intellectual property’ restricts the exchange of information between scientists. It is at this time (and a bit later at museums, and other institutions) when data are recognised as a tradable commodity. Consultants often try (and many still do) to ‘protect’ the data they accumulate, even if its collection is paid for by the client. This obviously has significant consequences for the overall scientific enterprise. The Albany Museum also tries to sell their freshwater invertebrate data because at the time they are desperate for funds. After a great deal of to-ing and fro-ing between DEAT and the museum, it is established that institutions may not sell data collected with public money, or records curated using public money. This is quite a tricky issue, but an important one.

4.3.2 International isolation

During the 1980s, many South African scientists experience a degree of imposed isolation from the rest of the world which results in difficulty in trying to link up with individuals and groups from other countries. However, Dirk Grobler and Mike Silberbauer visit the USA in 1981 to gain knowledge about water quality modelling, and are extraordinarily fortunate to have discussions with Steve Chapra, Dick Park and Bob Ambrose. Their most serious difficulty is that the only way that they could visit the US Army Corps of Engineers is on the guided tour of the public exhibits. They get around this by consulting a team of former Core of Engineers employees.

The Hydrological Research Institute is also privileged to employ students and graduates from UK Colleges such as SILSOE. Jackie King recalls that when she tried to establish links with overseas scientists, especially from the US and Australia, she would receive responses such as: “*The only reason I am responding is to say that I am not talking to South Africans*”. As a result of this isolation, South African scientists have to work more closely with each other. On the positive side, this isolation also stimulates many South African scientists to be far more innovative in developing new equipment and approaches to solving problems.

In 1984 a Group for Aquatic Productivity (GAP) meeting to be held in Durban – organized by Richard Robarts and a local committee – is internationally boycotted and has to be cancelled. In 1988, Johan Grobbelaar, a member of SIL GAP, is refused permission to attend the meeting in La Rochelle, France. This leads to some international diplomatic rumbling and the organizers decide that he could attend if he was a ‘Brit’ working in South Africa. Finally, he is allowed to attend on the proviso that nowhere will it be mentioned or indicated that a South African citizen attends the workshop. About this time the journal, *Algology*, refuses to publish a paper because the senior author was from South Africa. Tamar Zohary recalls that at an international conference on photosynthetic prokaryotes held in the Netherlands in 1988 there was huge opposition against her showing a film on her research on Hartbeespoort Dam, and the feeling of alienation is particularly difficult. During the mid- to late-1980s it was practically impossible to have papers published in the leading limnological journal, *Limnology and Oceanography*, of the American Society of Limnology and Oceanography.

This era is before the advent of the Internet and the practice of that time was to request reprints of papers from authors via postcards and the normal postal system. With South Africans experiencing difficulty to access international literature and methods, they start to develop their own methods. The relative isolation from the global knowledge pool results in a number of novel developments, which in turn arouses a lot of interest from overseas researchers at the end of the isolation period. Many scholars want to come to South Africa for conferences and learn from South African scientists. This was against the policies of most international funding institutions that did not recognize that it was possible to learn from a 'developing country'!

Around 1990, the first professional staff members from 'race groups other than White' began working in HRI's remote sensing and GIS section.

The WRC organises the first 'post-isolation' tour to Australia in 1991 during which common ground is found with Australian researchers working on environmental flow requirements. This is followed by a reciprocal visit to South Africa by an Australian delegation in 1994.

4.3.3 Social cohesion

From the middle 1980s, Fred van Zyl leads a DWA initiative on conducting 'water resource situation analyses' for a number of rivers across South Africa. Consulting engineers are appointed to conduct these studies, which focus particularly on quantifying the available water and the anticipated future demands for water. In 1986, Fred initiates an excursion (the so-called 'Kruger Rivers Trip') for those consulting firms that are responsible for catchment studies on rivers traversing the Lowveld. Teams from these firms and officials from DWA travel in convoy from south to north stopping at various sites along each of the rivers in question. The group is guided by Freek Venter and Andrew Deacon of Kruger National Park to facilitate access to sites in the park. In an innovative move for that time, Fred appoints one ecologist per river to provide the relevant consulting firm with an ecological perspective. These river ecologists are Charl Bruwer (Crocodile River), Bryan Davies (Sabie River), Mark Chutter (Olifants River), Pete Ashton (Letaba River), and Jay O'Keeffe (Shingwedzi and Luvuvhu rivers). Each of the consulting firms also has an environmental scientist or GIS specialist who liaises closely with the ecologist.

This field excursion is seen as a milestone event in changing and broadening DWAF's perspective from rivers and aquatic ecosystems being regarded as an 'equally competing user of water' to rivers being the resource base that provide a finite amount of water for various uses. The site visits and associated intense discussions between engineers, hydrologists, water resource managers and ecologists provide an important impetus for the development of new insights into the structure, role and importance of aquatic ecosystems and the need to define the environmental flow requirements (in terms of both water quantity and water quality) of rivers. On a question by Fred as to what is the minimum amount of water that should be left in the river to protect its functioning, one ecologist replies that the flow at the easternmost riffle in each river (*i.e.* closest to the Mozambique border) should be at least ankle deep. Seeking more precision and perhaps thinking of the tall frame of Charl Bruwer, Fred asks whose ankle would represent the correct depth. The ecologists reply that, as a rule of thumb, Mark Chutter's ankle will suffice.

During the early 1990s, an exceptionally constructive and complementary relationship exists between water resource managers from DWAF (mainly engineers) and the aquatic science community. There is also a healthy cohesion between aquatic scientists from all of the main universities across South Africa. The good relationships and cohesion within the aquatic science community are witnessed, as an example, during the 1990 LSSA Conference in Bloemfontein. Managers and scientists engage in lively debates during conference sessions and many professional relationships extend to personal relationships. In the evenings, conference delegates from across functional and organisational boundaries gather in rooms with televisions to watch the 1990 Soccer World Cup. The South Africans unify their support behind Cameroon in the absence of having a local team in the tournament at that time.

Over the years, Maitland Seaman at the University of Free State draws caricatures of many of the well-known members of the limnological fraternity in South Africa, associating each person with a particular organism or activity that they were working on. A selection of these caricatures is shown in **Figure 3**.

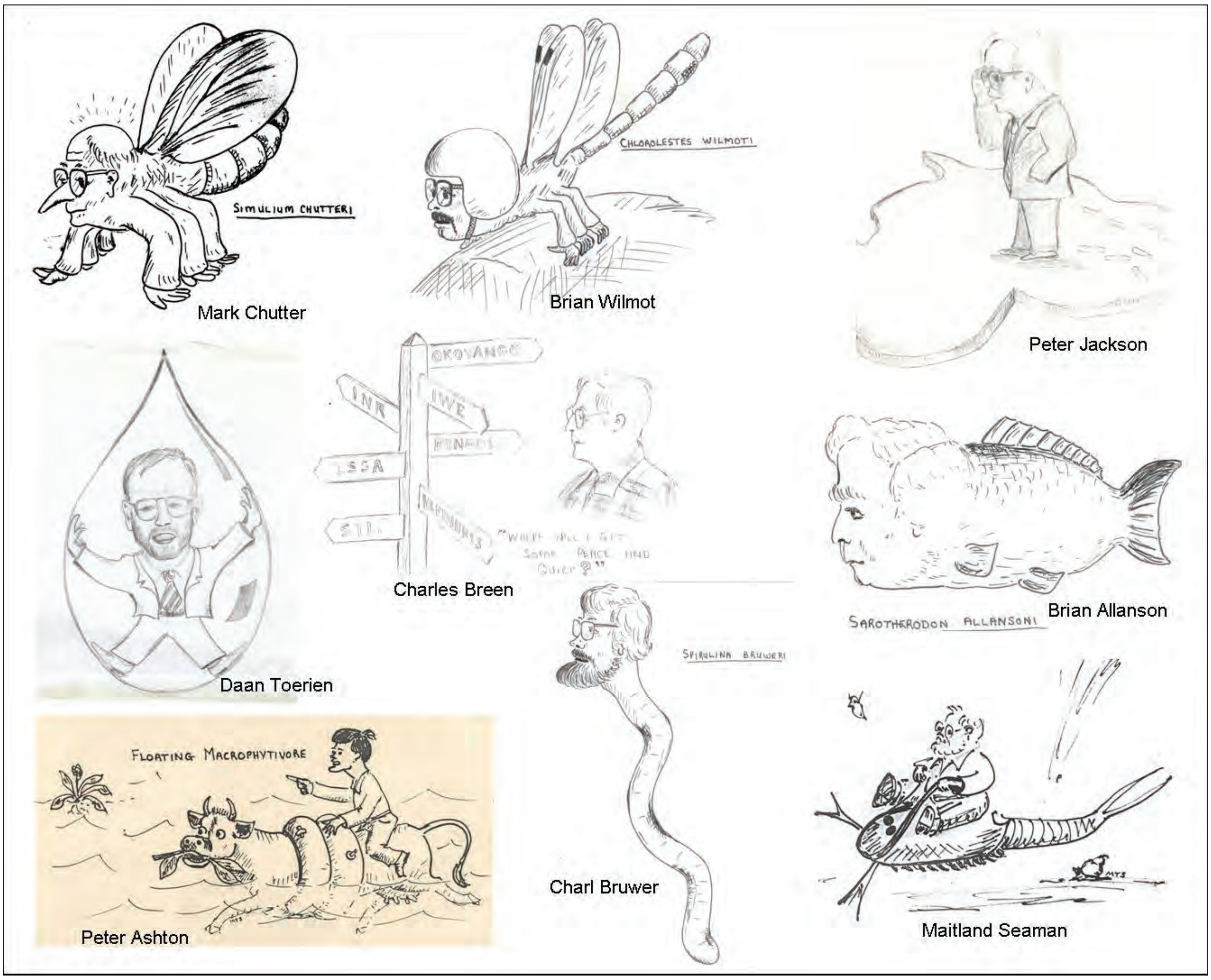


Figure 3. Caricatures drawn by Maitland Seaman of some of the well-known 'personalities' who were active in aquatic sciences during the 1970s and 1980s.

During the late 1980s or early 1990s, LSSA changes its name to Southern African Society for Aquatic Scientists to create a forum that will attract the involvement of marine and estuarine researchers and because the term 'limnology' is seen to be too narrow to adequately describe all of the different types of water-related work being carried out by society members. Also, non-limnologists do not know what the word means and the society wants to include managers and marine scientists within the group.

The WRC Steering Committees play important influential roles in helping to establish and maintain professional networks between researchers and water resource managers. When ecologists are first involved in WRC projects (and Steering Committee meetings), the Ladies' toilets are located right at the back of the building, while the Gents' are located close to the committee meeting rooms. Jenny Day is told by one of the managers that when the building was designed, the Ladies' loos were located where most of the secretaries' offices were; no-one thought that women would one day actually be members of Steering Committees!

4.3.4 Research culture

Continuing from the previous era and for the first half of this era, Heads of research units and university departments wield a lot of influence, power and authority. They decide who to appoint and carefully chose students and staff members so that they are often surrounded by very competent people. Post-graduate students are schooled on the basics of good science and the over-riding importance of excellence in all aspects of research. Brian Allanson epitomised this culture of excellence, with those who study under him remembering all too well that student and staff have to reflect excellence not only in their work but in the way they dressed, talked and walked. Such was his influence that some refer to this period as the 'Allansonian years'!

Fred van Zyl in DWAF was pushing for new answers to questions of how much water is needed to sustain aquatic ecosystems. His threat that he would "*make up the numbers myself*" if the scientists would not give him something useful and defensible to work with was a great incentive for people to give the 'best available information'. During this time, scientists become far more comfortable with producing a requisite simplicity. However, the associated disadvantage was that a 'quick fix, best available answer' becomes the expected norm that attracts funding at the expense of more carefully considered fundamental research.

Projects within the CSP are typically conceptualised as part of larger programmes and not as individual projects. The normal funding cycles are for a three year period, with a fair assurance that another (second) cycle will be approved if good work is produced. This usually proves to be long enough for a good student to complete their PhD work. Most of the research within the programmes is carried out by MSc and PhD students, supervised by experienced researchers and academics. Funding is never abundant; this makes people think carefully about which components or themes are most the important and worthy of careful study. The focus on and support for PhD students provides 'cheap, high quality labour' and at the same time ensures ongoing originality and succession within the national scientific enterprise. But there are virtually no post-docs positions available.

The research administrators of the Co-operative Scientific Programmes and later Foundation for Research Development are very supportive. Research administrators such as Graham Noble of FRD measure themselves against the progress that their programmes make in relation to scientific developments internationally. During the early 1990s, many research managers (especially from WRC) are very encouraging and are involved in the day-to-day running of the different research programmes. Many of these individuals are also highly experienced in research. While some research managers are not necessarily regarded as the top scientists in their respective fields, they are seen to be passionate about their fields of science and the role of science in the service of society.

4.3.5 The Bill Williams post-CSP review

In 1989, the then FRD invite Professor W.D. (Bill) Williams of the University of Adelaide in Australia to evaluate the Inland Water Ecosystems Programme (IWEP). The IWEP is one of the first CSP research programmes to be formed and comprises seven programmes or groups of research projects on lakes, reservoirs, rivers, wetlands and pans. The resulting report (Williams, 1989) is classified as 'strictly confidential' and is only recently released by the NRF on a request to use it specifically for the purposes of this chronology project.

During his visit of approximately three weeks, Bill Williams was asked to: (a) review research which has addressed water resource management issues as part of the IWEP, and (b) comment on the state of limnology in South Africa. Professor Williams evaluates the seven major research programmes within the IWEP, namely: the Pongolo Research Programme, the Wuras Turbid Impoundments Programme, the PK le Roux Programme, the Wetlands Programme, the Rivers Programme, the Mgeni Programme and the Hartbeespoort Dam Programme. Each of these programmes consists of between 10 and 24 research projects.

Professor Williams comments that almost all major types of aquatic environments and categories of water management problems are addressed within this suite of research programmes (Williams, 1989). In relation to the seven programmes, his summary is that:

- Research within the Inland Water Ecosystems Programme (IWEP) has provided a broad scientific basis of knowledge concerning South Africa's inland aquatic resources;
- IWEP has achieved its own broad objectives, namely to initiate research that would help to understand the structure and functioning of South Africa's inland aquatic resources;
- In the course of attaining these objectives, substantial contributions to the scientific literature are made. At the same time, important research findings remain in the form of unpublished theses and the recommendation is that every effort should be made to have this research written up and published;
- Almost all of the research under review had involved post-graduate students and the IWEP had therefore provided a useful vehicle by which much limnological expertise is produced in South Africa;
- All of the research programmes have produced findings of value to water resource management. However, the degree to which research findings have actually been used and applied by water resource managers has varied considerably; and
- Although management styles across programmes and projects have varied, management of the majority of programmes and projects has been satisfactory.

In relation to the state of limnology in South Africa in general (Williams, 1989), Bill Williams has the following to say:

> "*In my opinion, and considered as a whole, South African limnology is in disarray. It is poorly funded, is failing to address certain important environmental problems, lacks a cohesive sense of direction, and its potential contributions to effective water resource management are grossly underrated. Additionally, many of its practitioners are dispirited and disillusioned, there has been a significant attrition from their ranks, and few young South Africans regard limnology as a secure and attractive career*."

> "*All of this might be comprehensible in a country with plentiful water of good quality; for this to be the case in a country wherein water is a basic resource in decreasingly short supply, seems incomprehensible. Limnology, as the science which, with hydrology, underpins effective water resource management, should be amongst the most carefully nurtured of all South African scientific enterprises; instead, the reverse seems to be the case*."

Professor Williams feels that South African limnology is seriously underfunded and that this has contributed to the severe attrition of qualified limnologists from the field and the inability to recruit and retain bright young limnologists. This situation is exacerbated by the dearth of post-doctoral fellowships and the relative inflexibility of funding for postgraduate studies. He finds it surprising that, under the prevailing circumstances, a core of South African limnologists still wish to remain active in the field of limnology! He also comments on the failure by relevant agencies to appreciate the fragility of South Africa's limnological manpower basis, and to nurture and grow the available expertise.

4.3.6 General

In 1984, the Southern Hemisphere Limnology Conference takes place at Wilderness. The importance of this conference is that it brought together limnologists from across the southern Hemisphere (including Australia, New Zealand, South America and southern Africa) for a two-week conference and workshop where issues of mutual interest and concern are discussed. The workshop proceedings appear as an FRD National Scientific Programmes Report (Hart and Allanson, 1984), while the papers presented at the conference are published in a special edited issue of *Developments in Hydrobiology* (Davies and Walmsley, 1985).

Reservoir and wetland limnology is effectively terminated by an almost total shift to river research – the reasons for this abrupt change were never made clear to the researchers involved in these programmes. Rob Hart continues as a lone and isolated reservoir ecologist, pursuing survey-type studies on some turbid KZN reservoirs and two clear-water Mgeni reservoirs. The research topic pursued is to some extent esoteric, attempting to investigate the causes for species switching between two calanoid copepods. He samples these reservoirs fortnightly for nearly a decade, generating an exceptional long-term data base. This leads to many publications, and as yet has been the only attempt in South Africa to examine phytoplankton periodicity in both traditional taxonomic and functional terms (Hart, 2006a). The findings have direct relevance to the emerging perceptions on the 'Cascading Reservoir Continuum Concept' (Hart, 1996). Rob Hart also identifies and develops an understanding of a universal growth rule for copepods (*e.g.* Hart, 1998).

In the Western Cape, under the guidance of Bryan Davies at UCT and Jeff Thornton of the City of Cape Town's Department of Scientific Services, Bill Harding transitions from a microbiologist to an aquatic biologist, specializing initially in algology – with input from Braam Pieterse and Archie (REM) Archibald, and then on eutrophication processes and cyanobacteria and their toxins. Bill identifies the conditions in the shallow coastal vleis of the Cape Flats as an ideal environment to study conditions in eutrophic and hypertrophic epilimnia. Several papers (*e.g.* Harding, 1996; Harding and Quick, 1992; Quick and Harding, 1994) underpin this work. In 1992 Bill and Geoff Codd of the University of Dundee in Scotland establish the first laboratory in Africa dedicated to the detection of cyanotoxins. This facility is successful and its mode of operation is cloned by Rand Water (Elsie Meintjies) and the Water Utilities Corporation of Botswana (George Senai). In addition to his work on wetlands and vleis, Bill's studies of the dams supplying water to Cape Town (Voëlvlei, Theewaterskloof, Wemmershoek and Steenbras) enable him to test his water quality modelling that later emerged as NEAP (Rossouw *et al.*, 2008).

During the early 1990s, new staff that join the Hydrological Research Institute have induction courses for limnological fieldwork, including boat handling, use of Secchi disks and sediment grabs, and how to take temperature and oxygen profiles.

Braam Raubenheimer (the then Minister of Water Affairs) – through his role as Chairman of the Board of the Water Research Commission – directs that the location used for WRC-funded research on rainfall stimulation *via* cloud seeding experiments be moved from Harrismith to Nelspruit. This suggests that he may have seen some potential benefits of this research to his farming enterprises located nearby at White River.

Wouter van der Merwe becomes Manager Scientific Services at the Department of Water Affairs in the mid-1980s. He works closely with Dirk Grobler and water quality monitoring becomes increasingly important. Wouter arranges for Professors Ward and Saunders to be brought in from the USA to deliver training courses on the design of water quality monitoring programmes.

In the days before personal computers and electronic forms of communication and data storage and transmission become available, libraries provide the main sources of information for the country's aquatic scientists. Dedicated individuals within the LSSA produce annual lists of limnological references, which prove to be exceptionally useful; this activity is later taken over by the WRC and the references are managed by the WRC's Waternet system.

The Computing Centre for Water Research (CCWR) based in Pietermaritzburg is pivotal in establishing an e-mail network and on-line hydrological data distribution system at a time when few people had computers on their desks.

Jim Cambray remembers wanting to take a photograph of the then Hendrik Verwoerd Dam (now Gariep Dam) wall during the 1980s; later he wanted to use the photograph for a chapter in the book *The Ecology of River Systems* (Davies and Walker, 1986). At that time the dam wall was classified as a strategic installation so approval for any photograph had to go through the military. In his application to use the photograph he noted that the Department of Water Affairs and Forestry had issued a booklet, *Taming the Orange River*, full of photographs of the dam wall including cross-section diagrams. This publication was freely available to the public. However, the generals flatly refused that such a photograph of the dam wall could be used in a book. Jim fought this one for several months and in the end the generals told his boss, Dr Neethling, the then Director of Cape Nature Conservation, that they would put him in jail for breaching security if Cambray used the photo! Well this put the end to his attempts because, understandably, he received quite a firmly written letter from Dr Neethling to drop the issue, although he admitted he did see Jim's point. That weekend in the Sunday Times the PPC cement company had a full two-page advertisement with almost the exact photograph of the dam wall that Jim wanted to use! These were the types of petty "security issues" that researchers often had to deal with in the 1980s.

5 THE LATTER YEARS – ADAPTING TO CHANGE (1995-2010)

5.1 Chronology of key events

1995 – Windows 95 is released

1996 – The Southern African Society for Aquatic Scientists holds its annual conference at the Victoria Falls, Zimbabwe in association with the International Symposium on Exploring the Great Lakes of the World (GLOW).

1997 – Publication of *Overview of Water Resources Availability and Utilization in South Africa*, by the Department of Water Affairs and Forestry (Basson *et al*., 1997).

1997 – White Paper on a National Water Policy for South Africa is accepted by Cabinet in May of 1997. The founding principles are equity and sustainability, with a focus on redressing past inequalities, while the notion of equity for future generations is important.

1997 – The Water Services Act (Act No. 108 of 1997) is promulgated (RSA, 1997).

1998 – Publication of the second edition of *Vanishing Waters*, by Bryan Davies and Jenny Day (Davies and Day, 1998).

1998 – The new National Water Act (Act No. 36 of 1998) is promulgated (RSA, 1998).

1998 – Publication by the WRC of Mark Chutter's review of research on the rapid biological assessment of water quality (Chutter, 1998).

1999 – The J.L.B. Smith Institute for Ichthyology becomes a National Facility under the auspices of the National Research Foundation and is renamed as the South African Institute for Aquatic Biodiversity, with Professor Paul Skelton as Director.

1999 – Professor Brian Moss from the University of Liverpool is contracted by Unilever to assess the state of research on eutrophication in South Africa (Moss, 1999).

1999 – The Greater St Lucia Wetland Park in northern KwaZulu-Natal is South Africa's first World Heritage Site.

1999 – The Centre for Aquatic Toxicology (CAT) is established at Rhodes University's Institute for Water Research, funded by Unilever.

1999-2008 – Publication of the first nine of the ten volumes of *Guides to the Freshwater Invertebrates of Southern Africa*.

2000 – Publication by the WRC of a global review of inter-basin water transfer schemes (Snaddon *et al.*, 2000).

2003 – During a frenzy of restructuring in the Department of Water Affairs and Forestry, the Institute for Water Quality Studies is renamed as Resource Quality Services.

2003 – Phase 1b of the Lesotho Highlands Water Project, the Mohale Dam and its tunnel link to Katse Dam, is completed. Water from this reservoir is pumped via a tunnel through the mountains to Katse Dam, from where it is delivered to South Africa. In later years, large volumes of this transferred water are abstracted illegally by farmers irrigating riparian crops along the banks of the Liebenbergsvlei and Wilge rivers that convey water from Lesotho to the Vaal Dam for supply to the Witwatersrand area.

2004 – A National Spatial Biodiversity Assessment provides the first comprehensive spatial assessment of biodiversity throughout South Africa. This assessment dealt with terrestrial, river, estuary and marine environments and highlighted the overall poor state of South Africa's river systems.

2004 – Publication of the National Water Resource Strategy (DWAF, 2004) with a key contribution by Bill Rowlston.

2007 – The Berg River Dam, the first dam in South Africa in which physical provision is made for flood releases for purely environmental purposes, is completed in the Western Cape.

2009 – Publication of *Water Resources of South Africa 2005*, providing an update of the Water Resources 1990 study, by the Water Research Commission (Middleton and Bailey, 2009).

2009 – The conference on International Environmental Water Allocations is held in Port Elizabeth.

2010 – The first full-scale International Limnological Conference to be held in Africa is held in Cape Town. Plenary papers are delivered by Rob Hart, Bill Harding and Peter Ashton.

5.2 Individuals and topics of note

By the mid-1990s, enthusiasm for remote sensing has given way to a more integrated approach to spatial data using geographical information systems (GIS). Eventually, in 2005, Google put the power of GIS, remote sensing and digital elevation models on the desk of everyone who could afford a PC and an Internet connection. For instance, SANBI commissioned the development of a wetlands classification system that could be used with remote sensing data to produce a national inventory of wetlands. Dean Ollis, Justine Ewart-Smith and other members of the Freshwater Consulting Group produced the classification, while John Dini (head of the Freshwater section of SANBI) and his colleagues have produced the first iteration of the inventory.

Bill Harding also studies the phytoplankton assemblages, particularly diatoms, of Western Cape vleis, wetlands and dams. The CSIR diatom research programme, headed by Archie Archibald and Ferdie Schoeman, has been terminated during the restructuring of the NIWR and its subsequent entity, Watertek. Archie is being retrained as a waste manager in the CSIR and Ferdi has moved to the Pretoria Zoo in disgust. The diatom collection is under threat after the untimely death of Archie Archibald and Ferdy de Moor approaches the CSIR offering to house it in the Albany Museum, Grahamstown. It is now curated by SAIAB but is currently on loan at the University of the North-West, where diatom research is being done. The long-term safety of the collection is now assured under the umbrella of SAIAB.

On-going research has produced a South African Diatom Index – which will become part of the OMNIDIA software which is used internationally. As of 2010, the Diatom Assessment Protocol is being rolled out as the fourth leg of DWA's River Health Programme Biomonitoring toolkit. A provisional index for use in wetlands has also been formulated and is in the process of publication.

Bill Harding finalizes his work on hypertrophic epilimnia, investigating the plagioclimatic conditions that typify continually-mixed lakes (*e.g.* Harding, 1996). In 1997, Bill leads the UN-FAO-CIFA investigation into the eutrophication status of African lakes (Harding and Thornton, 1997; Thornton and Harding, 2003). In 2000 he becomes the first Certified Lake Manager, accredited by NALMS, outside of North America. From 2000 onwards, Bill is instrumental in reviving WRC interest in reservoir lake studies – undertaking several projects and also heading the Hartbeespoort Dam Rehabilitation Study (Harding *et al.*, 2004). These studies develop the Nutrient Enrichment Assessment Protocol (NEAP), an internet-based software for assessing the eutrophication status and management needs of eutrophic reservoir lakes, and phosphorus loading limits for South African dams (Harding, 2008), a eutrophication-focussed guide for catchment-wide assessments (Rossouw *et al.*, 2008) and a detailed examination of the fish assemblages of eutrophic waters in Gauteng (WRC, in press). Arising from this work is also the first analysis of the potential for foodweb reshaping in South African dams (Harding and Hart, in preparation). Bill is also instrumental in promoting the revival of ways to use diatoms as water quality indicators (Taylor *et al.*, 2007a; 2007b).

5.2.1 Policy revision process

1994 sees the dawn of democracy on South Africa. The first minister of water affairs is Prof Kader Asmal, a South African legal academic who returns from exile in Dublin. There are urgent equity issues in South Africa, some of which hinge on the private ownership of water. The minister loses confidence in his technically strong senior public servants with regard to their societal intent. This leads to a strongly stakeholder-driven water law review process, side-lining many experienced public servants, and including innovative thinking and recent research results (Palmer, 1999). From an aquatic science perspective the key aspect is the appointment of a SASAqS member (Tally Palmer) to the Water Law Review Panel as the deputy chair and the provision of a great deal of technical input from SASAqS members throughout the country. The Finnish government provides funding – and some funding went to ensuring the most recent research outcomes – like the innovative South African methods on environmental flows – where the work of Jackie King and Jay O'Keeffe is crucial. These methods are inherently multi-disciplinary, drawing on local and contextual knowledge. A co-operative process with the Water Research Commission ensures the flow of current knowledge generation into the law review process. This creates the context in which Tally Palmer formulates the concept of the ecological Reserve, which emerges as a strong driver of water resource management policy both in South Africa and internationally (Palmer *et al.*, 2005). The then DWAF slogan: 'Some for all forever' becomes synonymous with the new, people-centred approaches to sustainable water resource management. SASAqS embraces the new vision of water resource management.

Few new people have entered the aquatic sciences scene and there is almost a lack of people to respond to the challenges posed by the new legislation. A confounding factor associated with finalization and acceptance of the new National Water Act in 1996 is that Cabinet required the Minister of Water Affairs to declare that no extra funds and capacity would be required to implement the new legislation.

SASAqS, as a Learned Society, becomes an active civil society body that helps to shape the future of water resource management and research in South Africa. Aquatic scientists in South Africa have been stimulated and 'grown' by the dominant thinkers of the previous era – Brian Allanson, Charles Breen and Jan Heeg were key figures. The Water Research Commission and their steering committees take over from the FRD programmes as the core collegial and peer review processes, and the WRC is the repository of most of the innovative research of the time – particularly that pertaining to environmental flows. This coalesces into science becoming a powerful driver in the societal process of water law review. The emergence of the building block and resource directed measures methods for describing the water quantity and quality requirements of the ecological Reserve underpin the confidence of water lawyers – of whom Advocate Francois Junod was the doyen and leading thinker and practitioner – that environmental requirements for aquatic ecosystems were legally defensible. Jackie King, Jay O'Keeffe, Kate Brown, Rebecca Tharme, and Denis Hughes are key figures in environmental flow developments. Francois' participation on the Sabie River environmental flow workshop is pivotal in this process.

In terms of aquatic science, the RDM process brings together the aquatic sciences community in an active period of practice-based research. The openness to multi-disciplinary understandings enable the recognition that flows can be translated into habitat through an understanding of geomorphology and hydraulics. Eventually there is the recognition that if flow is available but its quality is impaired, the ecological health would be low. Tally Palmer, Nikite Muller, Nico Rossouw, Andrew Bath, Heather Malan and Sebastian Jooste pioneer the environmental water quality methods.

5.2.2 Estuaries research

John Day's book *Estuarine Ecology with particular reference to South Africa* published in 1981 (Day, 1981) is followed by the book on estuaries edited by Alanson and Baird in 1999. Then there were the CSIR's green reports (1980s) with Pat Morant and Piet Huizenga and also John Grindley and Alan Heydorn involved. In Natal we have George Begg's seminal work (1980s) and Ricky Taylor's St Lucia work (summary of work in PhD thesis). Alan Ramm and Trevor Harrison develop estuarine health indices for DEAT.

The Consortium for Estuarine Research and Management (CERM) starts looking at estuaries as social-ecological systems in the early 1990s. This multi-disciplinary and multi-institutional research programme, funded mainly by the WRC, is driven by the question: what are the freshwater requirements of estuaries? CERM represents a unique development in aquatic sciences in the way that it promotes co-operation across disciplines, organisations and also between communities. Seminal papers that arise from CERM-coordinated work are on estuary classification (Whitfield, 1992; 1996), and estuarine importance ratings are published in the journal *Water SA* (Turpie *et al.*, 2002). The University of Port Elizabeth (UPE) started work on Eastern Cape estuaries in the early 1980s, with the university's Institute for Coastal Research obtaining funding from DEAT to work on the Nahoon and Buffalo estuaries at East London and on the Sundays River and Swartkops River estuaries near Port Elizabeth.

5.2.3 Kruger National Park Rivers Research Programme

As appreciation for the importance of flow in sustaining the aquatic and terrestrial ecosystems of the Kruger National Park gains credibility, DWAF convene a workshop in 1987 that envisions the Kruger National Park Rivers Research Programme (KNPRRP). The KNPRRP is initiated as a multi-institutional collaborative programme in March 1988. An earlier review (in 1992) had stressed the need for a more structured programme of research. The search for a theoretical foundation leads to the adoption of adaptive management as an organising framework for the research. This reflects a philosophical view expressed as:

"Decisions on management options need to be made in the context of historical and prevailing circumstances so as to optimise conservation of the natural environment of rivers. The basis for achieving this is our ability to predict the behaviour of these systems under changing circumstances. This acknowledges that, as trade-offs continuously have to be

made, there can be no absolute amount for water quality and quantity to sustain the natural environment indefinitely" (Breen *et al.*, 2000).

Charles Breen was appointed Programme Managing Director and leads the research initiative from 1994 to 1999. Sub-programme managers include Kevin Rogers, Andre Görgens, Harry Biggs, Jay O'Keeffe, Mark Dent and Freek Venter. Considerable progress is made in understanding the structure and functioning of river systems and the influence of the KNPRRP in the development and adoption of adaptive management is widely acknowledged. The final report records thirty two researchers whose approach to research was materially affected by the KNPRRP (Breen *et al.*, 2000).

The particular configuration of perennial rivers in north-eastern South Africa, traversing the Lowveld from West to East (through varying altitudes and land-uses), and crossing the iconic Kruger National Park before entering Mozambique, represents an attractive and practical study possibility – especially since it is becoming increasingly clear by the 1980s that many upstream influences are responsible for the declining flows and worsening water quality problems in these rivers (Joubert, 2007). The Park Warden of the Kruger National Park in the late 1970s and for most of the 1980s, Tol Pienaar, mentioned elsewhere in this report for direct aquatic science contributions, had petitioned government repeatedly to take action to correct various upstream factors (such as abstractions for a burgeoning irrigation sectors, industrial pollution, etc.) leading to these problems, but his pleas repeatedly fell on deaf ears. Eventually Tol resorts to strengthening the KNP's 'Water for Game' policy and gathers resources to build dams and increase water points for wild animals, even engineering a circular water pumping system to keep a small part of the highly biodiverse Sabie River (Joubert, 2007) 'alive' and flowing for anticipated periods when the situation became sufficiently critical. In practice this is never used, courtesy of the irrigators and other stakeholders who voluntarily kept the river flowing in the worst-on-record drought in 1992 (Biggs *et al.*, 2010). Dr Pienaar is thus instrumental in creating early formal awareness of the plight of these rivers. The 'river tour' (described elsewhere in this document) further strengthens the foundation for increasing scientific interest in these troubled river systems, and by the late 1980s it was fitting that the meetings to set up water quality standards are held in the Kruger Park (Joubert, 2007).

With core funding coming from the Water Research Commission, and a secretariat that was sponsored and housed by the NRF, the KNPRRP builds up a large list of participating agencies and universities. The first phase, until 1992, consists of a loose but potentially useful assemblage of projects driven by various enthusiasts. The second and third phases (co-ordinated by Charles Breen) are far more structured, the idea being to align studies and produce an organised foundation that leads to a useful decision-support system (DSS) believed to be necessary because of the continuing change foreseen in resources and needs in integrated catchment management. The core activities of Phase II include a desired state initiative (which led to a seminal publication establishing that concept: Rogers and Bestbier, 1997), an information management module, and a sub-programme comparing models / DSSs, plus what were considered more 'conventional' aquatic research topics. The programme stresses the importance of considering multiple scales, and stresses heterogeneity and dynamism (O'Keeffe and Rogers, 2003; Rogers and O'Keeffe, 2003). The third phase is designed to relate more to practical implementation. A central unifying approach of the programme from 1992 onwards turns out to be adaptive management, and the particular brand developed in the KNPRRP (Strategic Adaptive Management, or SAM) (Rogers and Biggs, 1999) proves to have an influence way beyond the programme. For instance, it sets the initial tone for the whole ecosystem management approach in the Kruger National Park and over the next decade for many other parks and natural (including water) resource management agencies (Freitag *et al.*, in review). Indeed this partly serendipitous influence can be considered one of the programme's greatest legacies. Many prominent participants (most of whom appear elsewhere in this report for other reasons) contribute to the programme in various ways, and further their own knowledge and capacity by collaborating with others and focussing on the key issues – to such an extent that it can be argued that the programme was an important part of the change mechanisms that led to a revised Water Act in the country (Biggs *et al.*, 2008), and to adaptive management praxis (Kingsford *et al.*, 2011). The programme becomes so well acknowledged (and deemed useful) that a standing joke was that everyone involved claimed parenthood! Indeed, it was a successful group effort. Apart from Charles Breen, other persons who continue after the KNPRRP for an extended period working towards the initiatives that follow were Kevin Rogers (Wits) Sharon Pollard (AWARD) and Harry Biggs (SANParks). Kruger appoints its first river manager Freek Venter, and he is followed by Thomas Gyedu-Ababio.

Around the turn of the 21st Century (some individual projects continuing for a few years), and in spite of continuing zeal, the KNPRRP is reluctantly terminated perhaps because it had set itself up as seeing an achievable endpoint ('the implementation phase'). Little did the participants realise then (a) how much durable influence they would actually have, but (b) that de facto 'implementation' has hardly begun. The slow-moving implementation of the National Water Act of 1998 took years longer than anticipated, to, for instance, proclaim the first catchment management agency – again it was no accident that this was the Inkomati agency, covering much of the KNPRRP's old stamping ground. Meanwhile, in the Kruger Park, a programme looking at landscape-ecological boundaries between riparian and upland systems 'continued' some of the KNPRRP's unfinished business. With further deterioration of rivers in spite of all the good work of the KNPRP, it is widely conceded that the KNPRRP 'should not have stopped'.

There are sufficient compelling reasons to take up the river research baton again, now under the name 'Shared Rivers Initiative' (SRI). The SRI focuses on understanding reasons for the lack of compliance towards meeting environmental flows, conducting action research, and improving social learning and governance – moving more towards how social and political research can enable the biophysical findings of the KNPRRP and beyond. This can be seen as a move towards a holistic or fuller socio-ecological system view. The small local NGO AWARD play a key role in SRI, uncovering key reasons for lack of compliance (Pollard and Du Toit, 2009) (for instance, one is poor legal capacity) and are already acting on these in the recently-launched Phase II of the SRI. Many other participants are gearing up for wider participation in an expanded Phase II. Another related project funded by the Water Research Commission is a strategic adaptive management project dealing in the 'full reality of the messy real world', by ensuring relevant feedbacks between various levels and scales in selected ICMA and other operating contexts. From this project it is startling to see that although agencies agree to adaptive practices, in reality, key feedbacks often do not happen. The principles embodied in this study are now integrated into operations regarding the Crocodile River. Along with effective visioning and planning, genuinely participatory techniques, appropriate modelling, and what are believed to be other critical success factors, these adaptive feedbacks make the outlook positive for reversing negative trends in the Crocodile River in the medium-term. The SRI and this adaptive feedback project can be seen as an effective continuation in the region of what the KNPRRP had originally intended.

5.2.4 Environmental water requirements

The 1900s are an era of global dam building, not least in South Africa where over 100 new large dams are built per decade through the latter half of the century. By the 1970s it is becoming apparent that the dams are bringing costs in terms of river degradation, as well as benefits. A new science begins to develop internationally, which aims to understand the links between flow and ecological processes in rivers and how these links can be weakened by water-resource developments. At first this scientific work largely by-passes South Africa because the country is in an era of scientific anti-apartheid sanctions as well as political and economic sanctions.

But the awareness that rivers are being severely degraded is nevertheless growing in the country. Construction of the Pongolapoort Dam in 1984 triggers a series of pre-construction studies of the downstream Pongola floodplain and how the impacts of the dam can be mitigated (Heeg and Breen, 1982). The studies are significant for creating awareness among senior policy makers of the value of ecosystem services and that aquatic ecosystems need water for their own maintenance.

In 1981, Paul Roberts, a senior DWAF water engineer, suggests that 11% of the freshwater demands of the country would be needed 'for conservation' (Roberts, 1981, 1983; King and Tharme, 1994). He acknowledges that his estimate is simplistic, and urges water engineers and scientists to do research to ascertain how much water is needed for the environment.

By the late 1980s, understanding has progressed to the point where aquatic systems are becoming a recognised water-use sector. The book *Management of the Water Resources of the Republic of South Africa* (DWAF, 1986) repeats the call for research to obtain accurate values on the water needed to maintain aquatic systems. In 1987, the scientists respond in a CSP-hosted national workshop *The Ecological Flow Requirements for South African Rivers* (Ferrar, 1989), where they collate all available national understanding on this topic. Two early ideas for assessing the flows needed to sustain river ecosystems emerge from the 1987 workshop: the 'Flow Simulation Method' and the 'Skukuza Method' (King and O'Keeffe, in Ferrar, 1989; O'Keeffe *et al.*, 1989; King and Tharme, 1994). These embrace two concepts upon which all the flow-assessment methods for rivers soon to be developed in South Africa are based:

- Rivers can be held at different levels of health (*i.e.* ecosystem integrity), allowing a mosaic of river conditions to be maintained across the country that reflects society's different requirements from different rivers; and
- In developing countries such as South Africa very large numbers of rural people may be subsistence users of the rivers, and so their livelihood issues must be included in the flow assessment.

Without it being realised at the time, the methods that began to be developed were revolutionary at the global level because they adopted a holistic approach, recognising that all parts of the flow regime and all parts of the ecosystem need to be considered. The first approach for rivers, the Building Block Methodology (BBM), was prescriptive, first identifying a desired future state for a river and then describing a pattern of flows to maintain that state (King and Louw, 1998; Tharme and King, 1998; King *et al*., 2000).

This approach was ultimately shown to be flawed because it could not answer questions about what would happen if the recommended flows are not provided. Importantly, however, it introduces a structured multidisciplinary approach to assessing flows for ecosystem maintenance. Core disciplines used in its application are hydrology, hydraulics, geomorphology, water chemistry, zoology (fish, invertebrates), botany (aquatic, marginal and riparian vegetation), sociology and socio-economics. Other biophysical and socio-economic disciplines will be included later as required.

The BBM is soon replaced by two approaches that could produce scenarios, but it remains popular internationally because of its simple approach and detailed User Manual. It also has a place in the water history of South Africa: its application in a flow assessment of the Sabie River in 1996 convinces the legal team writing what was to become the 1998 National Water

Act that water for environmental maintenance could be quantified and thus legally enforced. This law is discussed further below.

The scenario-based approaches – Flow Stressor Response (FSR: O'Keeffe *et al*., 2002; Hughes and Louw 2010) and Downstream Response to Imposed Flow Transformations (DRIFT: Brown and Joubert, 2003; King *et al.*, 2003; Brown *et al*., 2005) are developed from the mid-1990s and are used today for all of the more complex flow assessments carried out in South Africa. Supporting tools have also been developed:

- A desktop model that uses the results from the holistic methods to provide a quick estimate for planning purposes of the monthly volumes of high and low flows to maintain a river at different ecological classes (Hughes and Hannart, 2003);
- The SPATSIM (Spatial And Time Series Information System) framework (Hughes, 2004; Hughes and Forsyth, 2006; Clarke *et al*., 2009) that brings together many of the tools used in flow assessments; and
- A series of indices to assess Present Ecological State, such as the Fish Response Assessment Index (Kleynhans, 2007; Kleynhans and Louw, 2007).

From about 1989, flow assessments also began for estuaries. As was the case with the rivers, the method for estuaries is developed through application to a series of estuaries, each of which pushes thinking forward. By 1999 a structured method for assessing the freshwater requirements for estuaries has evolved, written by a core team (Adams *et al.*, 2002; Taljaard *et al*., 2003) with input from CERM (Consortium for Estuarine Research and Management), a group of researchers and managers who collaborate to promote the wise management of estuaries.

Method development to advise on the ecological water requirements for wetlands (Jordanova *et al.,* 2006; Rountree and Malan, 2010), water quality, ephemeral rivers (Seaman *et al*. 2010) and groundwaters, and on the social use of aquatic systems, is also at an advanced stage, with good interactions between the groups of specialists working on the different types of ecosystems.

With the promulgation of the National Water Act in 1998 it became a legal requirement to set aside water for the support of the nation's aquatic ecosystems. This milestone is followed by a second when the Directorate of Resource Directed Measures (RDM) is established within the Department of Water Affairs in 2002, to ensure adequate protection of these ecosystems. There are three main elements to the Resource Directed Measures: 1) a catchment-based classification system for water resources, which guides the setting of one of three management classes for each part of the catchment's water resources; 2) the Ecological Reserve, that is, the quantity and quality of water linked to each of those management classes; and 3) resource quality objectives (RQOs), which are quantitative and qualitative descriptions of the hydrological, chemical, physico-chemical, geomorphological and biological attributes that can be monitored for compliance of the management classes. The Ecological Reserve is, in effect, one of the RQOs.

More details on the above, including the history of the development of environmental water requirements in South Africa, and progress to date, are provided in a situation assessment of Resource Directed Measures 12 years after the 1998 NWA, is published in 2011 (King and Pienaar, 2011).

5.2.5 Response monitoring and the River Health Programme

The water quality and aquatic ecology studies of the late 1980s and early 1990s culminate in the development of national water quality guidelines for aquatic ecosystems (DWAF, 1996b). These studies also lay the scientific foundation for the launch of the River Health Programme (RHP) in 1994, bringing together scientists, water resource managers and stakeholders from a range of river systems across the country.

Until the late 1980s, water quality managers rely almost entirely on information gained from the monitoring of chemical and physical water quality variables. Such 'stressor monitoring' focuses on the stressors that are likely to cause pollution or other environmental change. However, a predictive ability is only possible where a known cause-effect relationship exists between the concentration of a specific stressor and the responses within a receiving ecosystem. Although the effects of a single substance on a single species under controlled conditions can be determined with reasonable confidence in a laboratory, the extrapolation of such effects to complex ecosystems is fraught with problems. Furthermore, the suite of analyses was focussed on determinands that were important mainly to agriculture, so includes a number of easy-to-measure (*e.g.* the individual major ions) but excludes biologically important measures like chlorophyll, turbidity, total N and total P.

Acknowledging the limitations of a stressor-only approach, water resource managers from DWAF start to consider response-monitoring as a complementary approach. Response monitoring entails the use of biological or environmental indicators to characterise the response of the environment to a stressor or disturbance. The response-oriented approach can be diagnostic, in that it can indicate how well an ecosystem is functioning given the degree to which it is subjected to multiple stressors.

While response monitoring makes sense conceptually, water resource managers still have to be convinced of the practicality and value of this new approach. Dr Henk van Vliet, then Director of DWA's Institute for Water Quality Studies, is instrumental in lobbying in favour of introducing this new approach among his colleagues at DWAF's Head Office – most of whom had engineering backgrounds. Work such as in the United States on fish communities (Karr *et al*., 1986) and in Great Britain on macro-invertebrates (Wright *et al*., 1984) demonstrate that response monitoring can provide valuable and useful information.

In South Africa, Mark Chutter's development of an invertebrate-based index of water quality (Chutter, 1972) largely escapes the notice of local water resource managers. In practice, the original Chutter Index (Chutter, 1972) requires specialised, time-consuming species-level invertebrate identification, which makes it expensive to apply in later years when research became more commercialized and funds for field work decline. Mark Chutter's extraordinary knowledge of South African rivers and their invertebrates ultimately enable him to develop the first version of the South African Scoring System (SASS), a technique that uses riverine invertebrate assemblages to estimate water quality; later variants of this system are now used nationally for various monitoring purposes.

In the USA, the development of simpler and quicker field techniques – known as rapid bioassessment protocols – for the routine use of biological indicators (*e.g.* Barbour *et al*., 1999) greatly increase the attractiveness of response monitoring. Henk van Vliet initiates the development of a new South African monitoring programme by commissioning the CSIR to develop a conceptual framework for such a programme (Hohls, 1996). The programme is initially called the National Aquatic Ecosystem Biomonitoring Programme (NAEBP). Mark Chutter is funded by the WRC to develop a rapid, invertebrate-based bioassessment tool, SASS (the South African Scoring System; Chutter, 1994; 1998). This index is widely tested, refined and used, with notable work done by Chris Dickens and Mark Graham (Dickens and

Graham, 1998; 2002) as well as Helen Dallas (Dallas, 1997; Dallas and Day, 2007). The SASS system has since become the basis of much river biomonitoring across the country.

An early focus on river ecosystems leads to the establishment of the River Health Programme (RHP) as a sub-programme of the NAEBP. The first objectives for the NAEBP still apply, namely to:

- Measure, assess and report on the current state, as well as the spatial and temporal trends of change and emerging problems of aquatic ecosystems; and
- Ensure that all reports provide scientifically sound and management-relevant information for national aquatic ecosystem management (Roux, 1997; Murray, 1999).

The Department of Environmental Affairs and Tourism (DEAT) and the WRC become early partners in the RHP, and are later referred to as the 'national custodians' of this development. Realising that the national departments do not have sufficient numbers of competent staff to implement a national biomonitoring programme, the national custodians sought the support of provincial implementation agencies. During a 'consultation planning meeting' in 1996 (DWAF, 1996a), provincial champions are nominated to lead clusters of provincial departments and agencies in implementing the RHP across the country.

In parallel with the development of provincial implementation capacity, the national custodians provide funding to stimulate the development of various biological indices and protocols for selecting monitoring sites, deciding on monitoring frequency, processing data and reporting information. Scientists from UCT are prominent in developing spatial classification of rivers and protocols for the selection of monitoring and reference sites (Brown *et al*., 1996; Eekhout *et al*., 1996), while Rhodes University played a prominent role in reviewing and recommending ecological indicators for use in the programme (Uys *et al*., 1996).

Neels Keynhans is a central figure in the development of several methods for, and their application in, the RHP. His developments include an index for assessing habitat integrity (Kleynhans, 1996), a fish-based index (Kleynhans, 1999), an ecoregional classification for rivers in South Africa (Kleynhans *et al*., 2005; 2007) and the more recent development of methods to determine the EcoStatus of rivers. These methods will no doubt increase in value once they have been scientifically validated by other aquatic scientists and the techniques have been more widely disseminated.

During the late 1990s and early 2000s, a key priority is to promote adoption of the RHP by provincial agencies and implementation teams. As more and more provincial government agencies experiment with implementing the programme, valuable lessons regarding successes and mistakes are shared with other provinces. At the same time, new developments funded by the national custodians have to be communicated to provincial implementation agencies. Mechanisms to facilitate communication horizontally between provinces and vertically between provincial and national agencies include annual meetings of all role players, technical reports, a newsletter and a dedicated website (www.csir.co.za/rhp, now hosted at www.dwa.gov.za/iwqs). Bonani Madikizela and Ramogale Sekwele at RQS are instrumental in ensuring that the RHP attains the status of a formal DWA national monitoring programme during the early 2000s.

A comprehensive overview and list of references pertaining to the RHP can be found in Roux *et al.* (2008).

5.2.6 Conservation status and systematic conservation planning

Since the 1970s, and at about 10-year intervals, four freshwater conservation plans are developed for South Africa, using different but broadly advancing approaches to conservation planning. In the 1970s, Graham Noble evaluates the conservation status of some 40 aquatic biotopes classified according to a mixture of biological and physical attributes. These attributes include dominant vegetation type, geomorphological zonation, river size and flow variability. Based on this analysis recommendations are made for the conservation of 25 representative sites, identifying which of these had no formal protection at that time (Noble, 1974). This study is ahead of its time in many ways. It produced a protected-area gap analysis for aquatic biotopes and habitats of threatened species, an approach that would only be formalized in terrestrial conservation planning some 20 years later (Scott *et al*., 1993) and is still, to a large extent, lacking for freshwater systems. It also strove for efficiency in the use of conservation resources, attempting to minimize the number of sites selected by aligning freshwater sites where possible with areas that also contain important terrestrial conservation features. It diverged from more recent approaches to conservation planning, however, in that aquatic biotopes are descriptive rather than spatially explicit and the sites that were recommended for conservation are relatively well known by experts rather than being chosen through systematic analysis of the options across the entire landscape.

In the 1980s, 144 river sites of outstanding conservation importance in South Africa are spatially identified based on expert opinion of their importance (O'Keeffe, 1986; 1989). The map thus produced is intended as a starting point for conservation action, but also recognizes that 'until we can classify our rivers and river zones in detail, management of different priorities will at best be haphazard' (O'Keeffe *et al.*, 1989). In an attempt to be more quantitative and consistent, this project is followed by the development of an expert-driven River Conservation System to assess the relative conservation importance of different rivers and to communicate the results to decision-makers (O'Keeffe *et al.*, 1987; 1989). The River Conservation System was a semi-numerical Expert System in which several biological and physical attributes are weighted and scored based on expert knowledge and informed by quantitative data where available. The system offers flexibility over traditional scoring approaches in that it provides the user with rules that can be applied to change the relative importance of the weightings to different settings (*e.g.* regional differences in biota, differences related to river size). While the system provides a means of assessing relative importance of several rivers across a landscape, it seems to have only been applied in assessing the relative importance of three to four rivers at a time. This was possibly a consequence of the labour intensive approach and computing limitations at the time.

In the 1990s, the first national, spatially explicit and systematic conservation plan is developed for freshwater fishes in South Africa (Skelton *et al*., 1995). An extensive museum database of freshwater fish collections is fed into an iterative reserve algorithm to produce a minimum set of sites that would together protect each species at least once. Twenty quarter degree squares (15' x 15') of 'maximum importance' are identified. Although the adequacy of representing only one population of each fish species is questionable, and the planning units used are not as relevant to rivers as catchments would have been, the 20 priority sites thus identified broadly encapsulate the pattern of fish species richness, endemism and threat in the country.

In the 2000s, systematic planning principles drive the first comprehensive National Spatial Biodiversity Assessment (NSBA) that is undertaken for South Africa. The NSBA deals with terrestrial, river, estuary and marine ecosystems but not wetlands, which are too poorly known for an adequate assessment to be made. The NSBA highlights the overall poor state of South Africa's river systems (Driver *et al*., 2005), heightening the awareness in the conservation and water sectors of the urgency for strategic conservation action to protect South Africa's freshwater biodiversity. The development of policy objectives for facilitating cross-sector collaboration and coordination in the management of freshwater biodiversity (Roux *et al*., 2006) and an overview of prospects and challenges in freshwater conservation planning (Nel *et al*., 2009) provide further impetus to developing this new branch of science. Mao Amis and Jeanne Nel complete their PhDs in freshwater conservation planning, Mao from the University of Cape Town and Jeanne from Stellenbosch University. An important current project (known as the National Freshwater Ecosystem Priority Areas project and coordinated jointly by SANBI and CSIR) has since delineated national priority areas for conserving freshwater ecosystems (Nel *et al.*, 2011a).

5.2.7 Wetlands research

Wetland research started early – in global terms – when G. Evelyn Hutchinson, together with his wife Grace Pickford and their colleague Johanna Schuurman, examine a number of pans and other inland waters in various parts of the country. The resulting paper (Hutchinson *et al.,* 1932) is Hutchinson's first on comparative limnology and one of the first detailed papers on the subject anywhere in the world. While doing this work he becomes particularly interested in water bugs and in 1929 produces what is, to this day, one of the very small number of papers on the taxonomy of southern African aquatic hemipterans. Schuurman independently produces a detailed study of Florida Lake (Schuurman, 1932).

After a gap of 30 years, during which some taxonomic papers on wetland organisms are published, but nothing on wetlands themselves, Arthur Harrison publishes the results of his MSc thesis on some vleis of the south-western Cape (Harrison, 1962). For the best part of yet another 20 years, wetlands are mostly ignored as research concentrated on rivers and reservoirs. In their review of research needs of South Africa's inland waters, Graham Noble and Julian Hemens (Noble and Hemens, 1978) did not even refer to the word 'wetland', talking instead about vleis, floodplains, pans 'and other lakes of the interior'. They did, however, indicate that information is required on such systems from both practical and conservation points of view. The only person actively working on wetlands at the time is George Begg of the Natal Town and Regional Planning Department, who produces two detailed reports, one on the wetlands of Natal in general (Begg, 1978) and one on the loss of wetlands from the Mfolosi catchment (Begg, 1984).

Internationally, the 1970s saw the beginning of serious attention being paid to wetlands. The Ramsar Convention was initiated in 1971 and came into effect in 1975 (South Africa being the fifth signatory). In 1979, Cowardin and co-workers produce a classification system for wetlands for use by the US Fish and Wildlife Service; this system is still in use in the USA to this day (Cowardin *et al.*, 1979). The first serious scientific attention to South African wetlands in this new era began in 1983, when Charles Breen organizes a workshop on wetlands at the annual Congress of the Limnological Society of Southern Africa, held in Pietermaritzburg. The next issue (volume 22, part 2) of the *Journal of the Limnological Society of Southern Africa*, is devoted to a series of literature reviews and position papers on wetlands. The CSIR's National Co-operative Programmes are reconstituted as the Foundation for Research Development (FRD) at about this time and Danny Walmsley, who had been a manager with the Ecosystems Programmes of the CSIR, is instrumental in developing a National Wetlands Programme within the FRD. One of the initiatives within the programme is the development of the Wetlands Working Group in 1986. The group identifies the lack of a detailed wetland inventory and classification system as one of the most pressing issues. A Wetlands Inventory Workshop is held in 1988 but soon after that funding for the programme as a whole dries up and attention to a national wetland inventory is delayed for a further couple of decades. During this time, Mike Callahan, working for the CSIR in

Stellenbosch, began to develop a classification system for estuarine wetlands, concentrating on the south-western Cape in the late 1980s.

The National Wetlands Programme funds various research projects. For instance, Jackie King and Mike Silberbauer of the Freshwater Research Unit at UCT start a detailed survey of the wetlands of the south-western Cape, producing two papers (Silberbauer and King, 1991a; 1991b). The summary curtailing of the programme meant that other data from this project are never written up.

Fortunately when the Wetlands Programme disappear along with the other Ecosystems Programmes in 1989, Geoff Cowan, an employee of the national Department of Environmental Affairs (DEA), takes up the cudgels on behalf of wetlands. Keeping wetlands in the public eye, he is instrumental in DEA producing a series of newsletters, in designating several more wetlands to the Ramsar protocol, and editing and contributing to a synthesis on South Africa's wetlands (Cowan, 1995; 1999; Cowan and Van Riet, 1998). In 1998 he is elected as Chair of the Africa, Europe and Middle East Regional Council of W*etlands International.* Sadly it seems that Geoff Cowan is no longer involved in wetland management.

Coastal lakes receive a fair amount of attention from Brian Allanson's group at Rhodes University in the 1970s and 80s. The very successful programme on the ecology of Lake Sibaya is the nursery ground for a number of successful wetland ecologists, including Rob Hart (zooplankton) and Mike Bruton (fish). At about the same time, Clive Howard-Williams works on Swartvlei in the southern Cape, where he is soon joined by Bryan Davies, who arrives from Mozambique to take up a lectureship at Rhodes. Burke Hill and Robin Boltt work on several of the coastal lakes in southern Mozambique but the area soon becomes politically inaccessible from South Africa. Burke, whose chief interest was in the Knysna crab, *Scylla serrata*, leaves to join the CSIRO in Australia, where he continues a successful career for many years. Robin Boltt dies prematurely and South Africa loses an exceptional ecologist with his passing.

After a 20-year hiatus, funding for research on and management of wetlands increases substantially. First Rennies, and later Mondi, fund large wetlands programmes run by David Lindley in KZN and elsewhere, contributing to the restoration of thousands of hectares of degraded wetlands. More recently the Department of Environmental Affairs has taken on the co-funding of Working for Wetlands, an initiative designed to provide jobs as well as to rehabilitate degraded wetlands. Working for Water personnel from SANBI are instrumental in starting provincial Wetlands Fora, which allow wetlands specialists to meet regularly and which also provide contact with interested members of the public. Furthermore, yearly national meetings, known as Wetlands Indabas, are held since 1998, initiated by Fred Ellery, Donovan Kotze, Damian Walters, David Lindley, Peter Goodman, John Dini and Piet-Louis Gründling. Working for Wetlands still supports the Indabas, as well as producing an electronic newsletter, *Gumboot.*

As recently as 2003, wetlands are still seen as the Cinderellas of aquatic ecosystems in South Africa. The National Biodiversity Strategy and Action Plan (DEAT, 2005), which is published in that year, notes that too little information is available for a proper assessment of the conservation status of South Africa's wetlands. Since that time, things have improved considerably. SANBI appoint John Dini as Director of their new Freshwater Programme, leading to various initiatives that are designed to expand our understanding of the distribution and classification of our wetlands. These include a national wetland inventory conducted by Namhla Mbona. The Freshwater Programme is under-funded, however, so a deeper understanding of wetland ecology still remains elusive.

In recent years the Water Research Commission has contributed significantly to the funding of wetlands research, including the production of guide to the identification of wetland plants (Van Ginkel *et al.*, 2011) and freshwater algae (Van Vuuren *et al.*, 2006). After soliciting a strategic review of research needs (Malan and Day, 2005), Steve Mitchell, a research manager with the Commission, organizes and runs two large programmes, one workshop on wetland rehabilitation that produces a series of eleven reports, and the other focusing on tools for assessing the integrity and usefulness of wetlands (Malan and Day, 2010 and reports therein). The WRC also provides funds for initiating a wetlands classification system for South Africa (Ewart-Smith *et al.,* 2006). This system, which has since been further refined (SANBI, 2009), is designed to be used with remote sensing data to produce an inventory of wetlands for the entire country. Furthermore, SANBI is driving the National Freshwater Ecosystem Priority Areas (NFEPA) project to provide information for future biodiversity conservation plans.

The need to develop methods to ascertain the Ecological Reserve for wetlands contributes to some degree to a better understanding of wetland processes although the lack of funds continues to hamper the investigation of the underlying science. The initial manual (DWAF, 1999) is produced by Andrew Duthie, Donovan Kotze, Bill Harding and Gary Marneweck, while preliminary methods are also developed for ascertaining the desired water quality of wetlands (Malan and Day, 2005) and the degree of habitat Integrity (DWAF, 2007). Bioassessment tools using plants (Fynn Corry, Freshwater Research Unit, University of Cape Town, *personal communication*) and invertebrates (Bird and Malan, 2010; Day *et al.* 2010) have been investigated and one using diatoms (Bill Harding, DH Environmental Consulting, *personal communication*) is currently being developed. All of these assessment tools are yet to be tested in the field. Wetland delineation methods have been developed for South Africa and are currently in use.

A number of people have been involved, some for many years, in wetland research funded in other ways, and in management. Peter Goodman is ‘Mr Wetlands’ in KZN Wildlife, Maitland Seaman and his students have continued to work for many years on the temporary pans of the Free State; Jenny Day and her students have worked on temporary pans and their crustacean inhabitants in the Namib Desert and the south-western Cape; Piet-Louis Gründling’s chief interest is the conservation of peatlands. Donovan Kotze, Sharon Pollard and Fred Ellery and their colleagues bring a human dimension to the subject by examining the sustainability (‘wise use’) of wetlands, particularly by subsistence farmers, while Jane Turpie examines various aspects of the resource economics of wetlands and also produces a number of tools for assessing the value of wetlands.

Spike McCarthy, Steve Tooth and Fred Ellery, and some of Fred’s students, make important contributions to the understanding of wetland geomorphology throughout the subcontinent (Tooth *et al.*, 2002; McCarthy *et al.*, 2007; Ellery *et al.*, 2008; Grenfell *et al.*, 2009; McCarthy *et al.*, 2010). In addition, Spike McCarthy and Fred Ellery and their students carry out considerable research on the structure and functioning of the Okavango Delta in Botswana (*e.g.* Ellery and McCarthy, 1994; McCarthy and Ellery, 1998; McCarthy *et al.*, 1998; 2000). Donovan Kotze and colleagues deal with the classification of South Africa’s hydric soils and their vegetation forms (Kotze *et al.*, 1996; Kotze and O’Connor, 2000; Walters *et al.*, 2006; Sieben *et al.*, 2010), and various people from the University of the Free State (*e.g.* Van Huyssteen *et al.,* 2005) carry out detailed research on wetland soils at selected sites.

While some good work is done on wetland hydrology, it lags far behind the effort that has gone into understanding the hydrology of South Africa’s rivers. Some of the earliest hydrological work on wetlands (Slinger, 1988) was done on the Pongolo River as part of the Pongolo Floodplain study. Drew Birkhead, Chris James and Martin Kleynhans conduct detailed hydraulic modelling in wetlands, particularly Nylsvley, while long-term process-based modelling is undertaken by Simon Lorentz and Eddie Riddell, one of his PhD students at UKZN.

Christine Colvin and colleagues from the CSIR investigate the linkage between groundwater and wetlands, while Geordie Ractliffe, Helen Dallas and Dean Ollis are currently monitoring the surface biotas of groundwater-fed streams and wetlands, particularly in the Table Mountain sandstones of the Cape Province.

Most of the work on the invertebrates of wetlands has been done at the universities of KZN (Chris Appleton, Nancy Rayner and Michelle Harmer), Free State (Maitland Seaman and his students) and Jenny Day and her students at the University of Cape Town (*e.g.* Dallas *et al.*, 2006). All three groups have a particular interest in the invertebrates of temporary wetlands, probably because these unusual ecosystems are home to a suite of particularly interesting, and probably endangered, crustaceans.

5.2.8 Biological control of aquatic weeds

Five species of South American aquatic plants have been introduced into South Africa, all of which cause a variety of problems for aquatic ecosystems and water users, and warrant control (Hill, 2003). These species are: *Eichhornia crassipes* (water hyacinth), *Pistia stratiotes* (water lettuce), *Salvinia molesta* (Kariba weed), *Myriophyllum aquaticum* (parrot's feather) and *Azolla filiculoides* (red water fern). Many of these species have proved to be problematic in several tropical countries around the world and the economic and environmental losses caused by these weeds is considerable (Hill, 2003). Water hyacinth is widely regarded as the world's worst weed (Scott *et al*., 1979; Hill and Coetzee, 2008). Several studies are carried out on the biology, ecology and taxonomy of these species in South Africa (*e.g.* Ashton, 1977; 1982; Ashton and Walmsley, 1976; 1984) and on chemical control techniques (*e.g.* Scott *et al.*, 1979). Later, these attempts to control the explosive growth of these weeds focus on efforts to develop effective biological control programmes for each species (Cilliers, 1991a, 1991b; Cilliers and Neser, 1991; Cilliers, 1999; Hill, 2003; McConnachie *et al.*, 2003; Hill and Coetzee, 2008; Hill *et al.*, 2007).

The first biological control programme against *Eichhornia crassipes* is initiated in 1973 (Cilliers and Neser, 1991) and the later refinements of this programme are reasonably successful to the point that the biological control agents are also 'exported' to Lake Victoria in Uganda and Lake Chivero in Zimbabwe. However, inconsistent results in the biological control of *Eichhornia crassipes* – and the other problematic aquatic weed species – have been ascribed to variable climatic conditions, uncontrolled eutrophication of aquatic ecosystems, and interference from mechanical and chemical control programmes carried out in the same area.

Effective biological control programmes are now in place for all five of the important species of aquatic weeds in South Africa. However, the effective long-term control of these plants requires an integrated management approach that uses all appropriate control methods, with an additional emphasis on reducing the amounts of nitrogen and phosphorus nutrients that enter water bodies and promote rapid growth of these species (Hill, 2003).

5.2.9 Inter-basin transfers

Worldwide in dryland environments inter-basin transfers (IBTs, referred to as inter-catchment transfers in the National Water Resource Strategy (NWRS), DWAF, 2004) are seen by water resources planners as the most feasible solution to the skewed distribution of water resources in terms of human water demand. South Africa is no exception. The National Physical Development Plan, developed in 1975, and the Industrial Decentralisation Programme, aimed to achieve the "*orderly settlement of an ever increasing population on a finite land area with limited natural resources while avoiding over concentration of population or economic activity in certain places*". The Department of Water Affairs (DWA, 1986) responds by saying that adequate quantities of water can be supplied anywhere in the country, provided that the cost of the supply is acceptable, and that DWA will attempt to provide water within the existing tariff policy at points of development priority as and when required. It is, however, noted that the provision of water is only one of the economic factors to be taken into account when locating an industry. The imbalance between the occurrence of and requirements for water are evident when one reads in the NWRS (DWAF, 2004) that only one of the 19 water management areas (the Mzimvubu to Keiskamma WMA) is currently not linked to another WMA through IBTs. In addition to the IBTs linking WMAs, a number of other IBTs occur within WMAs. This inter-linking of river basins gives effect to one of the main principles of the National Water Act, which designates water as a national resource.

Up to the mid-1990s water resource planners give no consideration to the potential adverse environmental impacts of IBTs. The aim is to move water efficiently from where it occurs to where it is needed for industry and agriculture and towns. By the time that environmental concerns are taken into account in the late 1990s, the effects of IBTs on receiving waters in many parts of the country is probably irreversible. The rivers have been 'tamed' with dams and IBTs as the promotional literature of the time liked to say. Bryan Davies and Jim Cambray are two of the ecologists who insist from the beginning that the effects of IBTs on biodiversity and ecosystem conservation are considerable and unacceptable, at least without proper consideration of the environmental consequences of such developments.

But what were the environmental costs? In 1977, Cambray and Jubb report on fish moving alive through the 82 km-long tunnel between the Orange and Great Fish rivers. At the time molecular genetics was in its infancy and no genetic work is done before this major IBT is brought on line although, in hindsight, genetic information would have been valuable as several species such as the chubbyhead minnow (*Barbus anoplus*) and moggel (*Labeo umbratus*) are shared between the two catchments.

As a result of the efforts of ecologists for the last three decades or so, planners have become aware of the environmental impacts of IBTs. Any proposed IBT now requires an in-depth EIA, an idea that would have been unheard of (and probably rejected!) in the early 1970s.

5.2.10 Trans-boundary (shared) river systems and hydro-politics

The publication of John Pallett's book on *Sharing Water in Southern Africa* (Pallett, 1997) prompts a wider appreciation of the need for concerted efforts amongst southern African countries to reach agreement on equitable shares of water from river basins and lakes that are shared by two or more countries. This initiative is given added impetus by Namibian plans to withdraw water from the shared Okavango River and transport this water to the capital, Windhoek, to relieve the water shortages that had been caused by a prolonged drought in the central areas of Namibia (Ashton and Manley, 1999; Ashton, 2000; 2003). Additional emphasis on the need for countries to reach consensus on the equitable apportionment of shared water resources is provided by the widespread misconception elsewhere in the world that the next generation of wars would be fought over water, especially in drought-prone Africa (Ashton, 2002; Turton and Henwood, 2002). In fact, the reverse seems to be true because water is seen as an agent of healing, reconciliation and peace in most parts of southern, central, eastern and western Africa (Turton *et al.*, 2003). The strategic role of attaining security of water supplies in the social and economic development of a country becomes widely known as "hydro-politics" (Turton and Henwood, 2002; Turton *et al.*, 2004).

The last fifteen years have seen a strengthening of the awareness amongst southern African countries of the need to work together to jointly develop shared water resources and avoid situations where one riparian country is able to adopt a dominant position because of its economic or military strength (Pallett, 1997). This results in the adoption of the SADC Protocol on Shared Rivers (SADC, 2001) by all southern African countries, and which now guides these countries as to how all water development projects that are planned for shared river basins should be conducted, and how the countries should work together to reach agreement on equitable shares of water.

Another feature of the increased awareness of and interest in equitable apportionment and management of shared water resources is the renewed attention paid to the existing and proposed treaties and agreements between countries as a framework for water sharing (Kisten and Ashton, 2008; Kisten *et al.*, 2009). Similarly, the search for so-called 'lessons learned' that could be transferred from one shared river basin to another result in greater attention being paid to the characteristics of African and other shared river and lake basins (*e.g.* Turton *et al.*, 2005). Approximately 58% of South Africa's territory falls within river basins that are shared with neighbouring countries and almost every decision or action that influences the availability or quality of water within the South African portion of these basins affects the quantity of water and its suitability for use by our neighbours (Ashton *et al.*, 2008). This provides a strong incentive to South African water resource managers to work closely with their counterparts in Botswana, Lesotho, Mozambique, Namibia, Swaziland and Zimbabwe jointly to set up international treaties and river basin commissions that can guide collective decision-making on water resource development and management projects (Ashton *et al.*, 2006).

In future, it is inevitable that more water development projects aimed at improving the water security of individual countries will be undertaken. Several of the proposed projects are extremely large (*e.g.* water transfers from the Zambezi River or the Congo River to South Africa) and would require a high level of long-term co-operation between countries if such projects were to be launched. The initial bilateral agreements between Lesotho and South Africa over the several phases of the Lesotho Highlands Water Project (LHWP) are broadened to include Botswana and Namibia, with the formation of the Orange-Senqu River Basin Commission (ORASECOM). This is a good example of how southern African countries work collaboratively with their neighbours to improve their individual and collective water security positions (Kruchem, 2012). South Africa is also a member of other river basin commissions on the Limpopo, Incomati and Maputo rivers.

5.2.11 Molecular genetics

The study of systematics has been rejuvenated in the last couple of decades by huge advances in practical methods for examining the genetic relationships between individuals, populations, species and higher taxa. Such studies are particularly rewarding in the old Gondwanaland of the south-western Cape, where many rivers have existed for tens of millions of years and freshwater taxa have been isolated from each other for as long. Research by several biologists shows that, indeed, many of the taxa that are morphologically undistinguishable (or nearly so) may be genetically very distinctive. We thus have many more 'evolutionarily significant units' than 'conventional' species in some of our rivers. People who have contributed to these studies include Barbara Cook on amphipods (UCT); Barbara and her student Savel Daniels on crabs and Gavin Gous on isopods (University of Stellenbosch); Marcus Wishart on dragonflies, net-winged midges, stoneflies and galaxiad fishes (UCT and Griffith University in Australia); Duncan Stevens and Mike Picker on stoneflies (UCT); and Ernst Swartz and his colleagues on redfin fishes (SAIAB). The molecular work in many of these studies is performed with the assistance of Paulette Bloomer at the University of Pretoria.

5.2.12 Aquatic toxicology

It becomes evident that research on water allocations seldom includes an adequate appreciation of water quality, even though ecosystem condition and functioning are adversely affected if water quality is impaired. This early driver of research into the water quality requirements of freshwater invertebrates linked South Africa into the eco-toxicology community. The Unilever Centre for Environmental Water Quality at Rhodes University is modelled on the Centre or Ecotoxicology in New South Wales, Australia. Tally Palmer, Nikite Muller and Patsy Scherman pioneer the approach of ‘environmental realism’ in ecotoxicology with an experimental approach using river water in flowing water mesocosms, with local organisms exposed to both single chemical stressors such as salts and whole effluent mixtures. Concurrently, Hein du Preez, Johan van Vuren and Victor Wepener (Rand Afrikaans University, now the University of Johannesburg) investigate lethal and sub-lethal metal pollution using toxicological and bioaccumulation techniques, mainly on fish. Laetitia Slabbert (previously from CSIR, now retired) is a leader in toxicological research, and important partnerships at this time include those with Sebastian Jooste, an environmental chemist from DWA (RQS) and Professor Barry Hart (Monash University, Australia). Water quality modelling (Andrew Bath and Nico Rossouw at Ninham Shand) and water chemistry and biomonitoring (Jenny Day and Heather Malan at UCT, and Dirk Roux at the CSIR) become important research issues. Unfortunately, our understanding of water quality requirements within environmental flow assessments remains globally under-developed.

5.2.13 Systematics

Algae

Two formidable female algologists born in Cape Town within two years of each other are Mary Agard (Mamie) Pocock (1886-1977) and Edith Layard Stephens (1884-1966). Both study overseas, returning to long and successful botanical careers in South Africa, Mamie Pocock ends up at Rhodes University for many years, and Edith Stephens at UCT. Mary Pocock has a varied career, teaching at a number of different schools and universities in between mounting collecting expeditions into Africa. The most astonishing of these took place in 1925 when she and Dorothea Bleek, the Bushman philologist, spend six months crossing Africa from Livingstone in Northern Rhodesia (now Zambia) to Luanda in Angola – mostly on foot with a long train of porters to carry food and specimens because of a lack of any form of transport in the area. Mamie goes on to UCT to complete a PhD on the algal genus *Volvox* and its allies, a group with which her name is associated ever since. She spends her later years in Grahamstown, mostly associated with the Botany Department at Rhodes University.

Edith Stephens seems to have been less adventurous but was no less interesting a character. Jenny Day recalls meeting her when Jenny was a young second-year student at UCT and Miss Stephens an old lady of nearly eighty. She lived in an old Victorian house in Belmont Road, Rondebosch. Her front room, which would have been a sitting room in anyone else’s house, was a library-come-office, with a couple of uncomfortable chairs and several tall grey steel shelving units piled with reprints, papers, books, sunhats and dried mushrooms. When she was about to venture into the sun she would lift a pile of books and papers, grab the large straw sunhat buried underneath, punch the crown until it looked roughly head-shaped, and then jam it firmly onto her head. She was also a fungal fundi, often called on by members of the public to identify potentially edible – or potentially fatal – mushrooms. She had an ancient brass compound microscope that she used when identifying minute algae. Jenny recalls being asked to note the details of the eyespot of *Chlorella*, when all she could see was a minute green blob – the *Chlorella* cell – at the end of what seemed to be a very long tube.

Miss Stephens accepted her status as a botanical eccentric with glee. Jenny recalls her mentioning the occasion on which she was collecting algae in the then wetlands near to Valkenburg on the Black River. She had collected a glass jar of water containing algae and was peering at it with interest when a man in a white coat came up to her and asked her what she was doing. "*Collecting algae – just look at them*", she exclaimed, holding up what seemed to be a jar of plain water. The man said, "*Right, come along dear, time to get you home to breakfast*". He was a warder at Valkenberg, the local mental institution, and he had mistaken her for an escaped patient. The more she argued, the more sure he was that she belonged behind bars (even though she was a little person and unlikely to harm anyone except herself). It was only when she persuaded the authorities to phone Prof. Adamson, of the Botany Department at UCT that she was allowed to leave. By then she had been retired for some 25 years!

Dr Bela Cholnoky's diatom collection is retained by the CSIR and expanded by Drs Ferdie Schoeman and Archie (R.E.M.) Archibald assisted by Mrs Valerie Meaton until the late 1980s.

Plants

With the vast number of terrestrial plants in southern Africa it is not surprising that aquatic and wetland plants have not received a great deal of attention. Many wetland plants are widespread or even cosmopolitan and their systematists are also scattered around the world. Local botanists who contribute significantly to the taxonomy of southern African aquatic plants include Edith Stephens, after whom the Edith Stephens Nature Reserve in Cape Town is named; Amy Jacot Guillarmod, who writes many papers on the wetlands of Lesotho; Ted Schelpe (Schelpe and Anthony, 1986), who works on ferns, including aquatic ones; Dave Mitchell, who describes *Salvinia molesta* (the infamous Kariba Weed) and works on its autecology, and later moved to Australia (Ashton and Mitchell, 1989); Peter Ashton and Danny Walmsley who both work on the taxonomy and ecology of the invasive red water fern *Azolla filiculoides* (Ashton, 1977; 1982; Ashton and Walmsley, 1976; 1984); and Anna Obermeyer who, between 1966 and 1985, writes a series of 17 papers in the *Flora of southern Africa* on the major families of aquatic plants. Muthama Muasya, who works on the systematics of the Cyperaceae (Muasya and Simpson, 2002), is probably the only wetland plant systematist currently working in South Africa.

Good field guides to the aquatic and wetland plants of southern Africa are produced by Christopher Cook (Cook, 2004) from the University of Zűrich, and to the plants of the Okavango Delta by Karen and Fred Ellery (Ellery and Ellery, 1997), who are then at UKZN. The Department of Water Affairs also produces a simple guide (Gerber *et al.,* 2004) to the water plants around South African impoundments.

Rene Glen (UKZN) develops an invaluable annotated list of aquatic, riparian and wetland plant species and is currently completing a book on their identification. This will probably be published in the near future as a volume of *Strelitzia*.

Invertebrates
From a systematic point of view the different taxa of freshwater invertebrates have been unevenly treated. In general, the crustacean fauna is fairly well known. G.O. Sars, a Norwegian who never actually came to South Africa, had soil samples collected for him from the bottoms of dry wetlands and sent to him by post. To these he added water, and when the desiccated eggs hatched from the mud he described the species of copepod, ostracod and cladoceran that emerged. More recently Nancy Rayner (South Africa) has dealt in detail with the diaptomid copepods and Koen Martens (Belgium) with the ostracods, so these faunas are fairly well known, although many species of ostracod still seem to be undescribed. No-one has treated the cladocerans systematically and this group could do with a good revision. In the 1920s Keppell Barnard, working at the South African Museum in Cape Town (see **Section 1.5.2**), describes numerous species of phyllopod (Notostraca, Anostraca and Conchostraca) from South Africa and Namibia, and more recently Michelle Hamer, Luc Brendonck (from Belgium) and Chris Appleton add to the list of species in these taxa. Of the higher crustaceans, Barbara Cook (*neé* Stewart) revises the amphipods, Gavin Gous the isopods, and Barbara Cook and Savel Daniels the crabs; the taxonomy of shrimps and prawns seems never to have been seriously revised.

Treatment of the insects has also been uneven. Some are now very well known: the trichopterans, are studied by Marjorie Scott (see **Section 1.5.6**) and Ferdy de Moor; the odonates by Elliot Pinhey and Michael Samways; the plecopterans by Duncan Stevens and Mike Picker; and the ephemeropterans by John Agnew and Helen Barber-James in South Africa, as well as Pat McCafferty in the USA and Carlos Lugo-Ortiz in Puerto Rico. Certain beetle groups have been well studied although some of these urgently need to be re-examined. The best known are the dytiscids and noterids, studied early on by Joe and Joyce Omer-Cooper of Rhodes University, and more recently by Olof Biström (Finland). A few other relatively well known beetle families have been studied by taxonomists from overseas: the hydraenids by Phil Perkins (Museum of Comparative Zoology, Harvard); the gyrinids by Per Brinck (late of Sweden); and the elmids and dryopids by Harry Nelson (late of the Field Museum of Natural History, Chicago). By and large the adult dipterans are relatively well known but the aquatic larval phases are not. Furthermore, most of the systematists who dealt with aquatic dipteran families in South Africa have died in the last few years: Arthur Harrison (chironomids); Botha de Meillon (ceratopoghonids and culicids); Brian Stuckenberg (blephariceridss, athericids and rhagionids) and Willis Wirth (ceratopogonids). Happily, Maureen Coetzee (culicids: now of Wits University) and Ferdy de Moor (Albany Museum: simuliids) are still going strong.

It is likely that many new forms await description in the remaining insect groups. The hemipterans were last treated by Hutchinson in several papers published between 1928 and 1933; the megalopterans, and the neuropterans and lepidopterans with aquatic larvae, are known from only a few species.

Of the remaining phyla, certain snail taxa within the molluscs are well known because they are intermediate hosts of parasites of humans and their domestic animals. They have been studied by, amongst others, David Brown and before him by Matthew William Kemble Connolly, an army officer who spent his later years working on freshwater and terrestrial snails at the British Museum (Natural History). The distribution of these snails was studied intensively by a number of people such as J.A. van Eeden and S.J. Pretorius at the old Potchefstroom University (now University of the NorthWest). The rest of the freshwater molluscs are poorly known and the taxonomy of various bivalves, limpets and prosobranchs sorely needs to be tackled. Some attention has been paid to the rotifers by Bob Brain, who worked for many years as a vertebrate palaeontologist at the Transvaal Museum in Pretoria; to soil nematodes by the late Juan Heyns at the then Rand Afrikaans University; to leeches by the late Johannes Oosthuizen of the University of Pretoria; and to the hydracarines by

Chris Jansen van Rensburg, who was until recently a senior administrator at the Free State Technikon.

The taxa that have never been properly tackled, and therefore particularly need work, are the protozoans, the sponges, the hydras, the turbellarians, the gastrotrichs, the bryozoans, the cladocerans the bathynellids, the hydracarines, the hydrophilids, the larvae of most coleopterans, many small dipteran families, and the scirtid (= helodid) beetles. The oligochaetes and leeches, and molluscan taxa such as *Tomichia* and the limpets, urgently need revision.

The publication between 2000 and 2009 of a series of guides has been of huge benefit for the identification of southern Africa's freshwater invertebrates. The project, which began in 1985, was hampered by the difficulty in finding a publisher. In the late 1990s the Water Research Commission took on the funding of the project, led by Chris Dickens, and publication of the guide books, edited by Jenny Day and Irene de Moor. The guides are now available online.

As a result of the earlier NIWR river surveys, large collections of plants and animals are identified and many new species are described by local and international specialists. Invertebrates collected by researchers of the NIWR (CSIR) during the 1950s, the aquatic beetle collections made by Prof Joseph Omer-Cooper and his wife Dr Joyce Omer-Cooper, and the freshwater diatom and fish collections of Dr Rex Jubb, formed the beginning of the National Collection of Freshwater Organisms (later Invertebrates). Dr Marjorie Scott is the first curator, followed by Dr Ferdy de Moor, who has been curator since 1984, assisted by Dr Helen Barber-James. The collection, which comprises more than two million specimens, is frequently accessed by researchers from around the world and the collection and expertise provided by the staff is used by post-graduate students and researchers from a number of universities and conservation agencies in South Africa.

Frogs

The only monographic revision of southern African frogs seems to be John Poynton's *Amphibia of southern Africa: a faunal study,* (Poynton, 1964). Poynton, who worked in the Zoology Department at the University of Natal for many years, was the doyen of frog studies in this country. He retired to London and is still publishing regularly. As an aside, Poynton has always been interested in parapsychology and was President of the Society for Psychical Research in London from 2004 to 2007. Poynton's *béte noir*, Eddie van Dijk, a colleague at the University of Natal, also worked on frogs, later retiring to Stellenbosch where, at the time of writing, he was still living and publishing. Alan Channing writes prolifically on the biology and taxonomy of frogs. He and his students at the University of the Western Cape are currently the only people in the country doing frog taxonomy; they are also looking at the population genetics of some taxa. If data coming from the invertebrates is anything to go by, the population genetics of frogs should provide interesting information on historical distributions. Andrew Turner of CapeNature has recently begun to examine the population genetics of some Cape frogs but this work is still in its early stages.

Although new species continue to be found (about twelve between 1964 and 2010), the emphasis has now turned to the revision of the higher taxa by systematists from elsewhere: Alain Dubois from the Museum national d'Histoire naturelle in Paris and Alice Grandison from the Natural History Museum in London, for instance. As a result of this work, many familiar names have disappeared, with new and unfamiliar ones such as *Afrana*, *Amietes*, and *Capensisbufo* taking their place.

As well as JC Poynton's 1964 monograph, several books on southern African frogs have been published since the 1960s: Walter Rose's *The Reptiles and Amphibians of Southern*

Africa (Rose, 1962); *V.A. Wager's The Frogs of South Africa* (Wager, 1965); and Neville Passmore and Vincent Carruthers' *South African Frogs* (Passmore and Carruthers, 1979). A frog atlassing project, modelled on a previously successful Bird Atlas project, was initiated in 1995 and run through the Avian Demography Unit (now the Animal Demography Unit) of the University of Cape Town. The results are published in the *Atlas and Red Data Book of the Frogs of South Africa, Lesotho and Swaziland* in 2004 (Minter *et al.*, 2004), a valuable volume that provides useful taxonomic and distributional data for frogs for the entire country. Most recently Louis du Preez and Vincent Carruthers have produced an important new book on southern African frogs: *A Complete Guide to the Frogs of Southern Africa* (Du Preez and Carruthers, 2009).

Fishes

Much of the information provided here has been drawn from the first edition of Paul Skelton's book: *Freshwater Fishes of Southern Africa* (Skelton, 1993) and its subsequent revision: *A Complete Guide to the Freshwater Fishes of Southern Africa* (Skelton, 2001).

In the nineteenth century most of the descriptions of South African fishes are by overseas naturalists, some of whom did, admittedly, explore the region in person. William Burchell, the English explorer and naturalist, was the first to describe freshwater fishes from South Africa. In the account of his 1822 travels he describes the sharptooth catfish, *Clarias gariepinus,* and the smallmouth yellowfish, *Barbus aeneus.* Some years later, in the 1840s, the German biologist Wilhelm Peters describes a number of species he had collected in the lower Zambezi River in Mozambique, as well as a couple of species from the Cape. Several more species are described in the 1840s by Andrew Smith, a medical doctor who was the first superintendent of what would later become the South African Museum. In 1861 Francis (François) Castelnau, the French Consul at the Cape, describes a further 21 species, including one that later turned out to be a naturalized goldfish!

John D. Gilchrist, then Head of the Zoology Department at UCT, and W. Wardlaw Thompson, his assistant, produce the first catalogue of freshwater fishes in 1913-1917. As well as publishing on numerous invertebrate taxa, both marine and freshwater, Keppel Barnard revises the fishes of the Cape and describes several new species in 1938 and 1943. In 1947 he publishes a *Pictorial guide to South African fishes* (Barnard, 1947).

As Paul Skelton notes (Skelton, 2001), until 1950 most ichthyological work in South Africa came out of the South African Museum in Cape Town. Since then, Grahamstown is synonymous with South African ichthyology, with important work being done at the Albany Museum and Rhodes University, largely under the direction of Rex Jubb, and later at the JLB Smith Institute for Ichthyology, under the direction of Margaret Smith. In 1999 that institution becomes the South African Institute for Aquatic Biodiversity (SAIAB). Under the direction of Paul Skelton, it continues to be the home of South African fish taxonomy to this day.

Important books on South African fishes include Rex Jubb's *Freshwater fishes of southern Africa* (Jubb, 1967), Bob Crass's *Fishes of Natal* (Crass, 1964) and *Trout in South Africa* (Crass, 1971), and Paul Skelton's books on freshwater fishes (Skelton, 1993; 2001).

Genetic studies

Modern systematics is far more than simple descriptions of species; today, genetic studies are crucial for understanding the relationships between taxa. Genetic studies of a number of different taxa, from amphipods (Barbara Cook) and isopods (Gavin Gouws) to crabs (Barbara Cook and Savel Daniels), and from dragonflies (Marcus Wishart) and stoneflies (Duncan Stevens) to fishes (Ernst Swartz and Marcus Wishart), are beginning to tell a story of long periods of genetic isolation, numerous cases of sibling species, and relationships between taxa that are much more complex than we ever dreamed of in pre-DNA days.

5.2.14 Fish biology

Between 1992 and 2006, Pierre de Villiers manages the Gariep Dam State Fish Hatchery. His work revolves around investigating the biology, ecology and culture of fish species indigenous to the Orange River system. Results are used when calculating the in-stream flow requirements for indicator species in both the Orange and Vaal River systems. Good communication links are set up with aquaculture research and management in South Africa resulting in processes being put in place to ensure environmentally friendly policies for aquaculture. Between 1996 and 2006, Pierre de Villiers also champions the River Health Programme in the central region of South Africa. Between 1997 and 2006 he also initiates, manages, assesses and monitors commercial net fisheries in State-managed dams on the Orange-Vaal River system. This provides crucial information to South African authorities about the potential to utilize these species and the most environmentally friendly methods to capture them. A policy document is drawn up by Pierre de Villiers and Mick Angliss and is presented at a SASAqS conference.

In 1997, Pierre de Villiers helps initiate and sustain the National Yellowfish Working Group, together with Dean Impson and executive members of the Federation of South African Flyfishers (FOSAF). This group has met annually since 1997 and produces annual proceedings and, with WRC funding, produces a national state of yellowfishes report. A crucial part of this programme is providing a platform for communication between the different conservation Departments and the private sector. Pierre has since managed the Orange Vaal River Yellowfish Conservation and Management Association and other similar river conservation initiatives. This involves the implementation of Yellowfish Conservation initiatives in the various rivers in South Africa. The Orange-Vaal River Yellowfish Conservation and Management Association received International recognition in a Society for Conservation Biology publication. A management committee consisting of Government officials and the private sector meets four times a year. Priority projects are identified and funding is sourced. Problems are also identified and processes established to manage these. This Association is active in accessing funding for various research programmes such as research on yellowfish genetics (Anglo Gold Ashanti), taxonomy (WRC), early development and growth studies (WRC), telemetry (WRC and Fly Cast Away) and socio-economic value (WRC). Association members assist with the management of these projects. This leads to active participation by anglers, landowners and industry. The annual YWG Conferences provide an ideal base for communication with the broader stakeholder groups. The conservation concept of catch-and-release of indigenous fish species originates here (flyfishing for freshwater and marine species). Support is provided to other such initiatives such as ERICA (Mpumalanga) and the Cederberg Corridor (Olifants River – Western Cape) sharing experiences and lessons learned.

Pierre de Villiers has coordinated the CAPE Estuaries Programme since 2006. He is instrumental in managing this World Bank programme in such a way that it is now embedded in all Government Departments mandated to be part of the overall management of estuaries in accordance with the Integrated Coastal Management Act (Act No. 24 of 2008). The programme is used to ‘set the scene’ for the design of the Estuary Management Protocol and the implementation of estuary management plans specifically and the ICMA in general. A national estuary database is set up within SAEON and an accredited estuary management training course is presented by Nelson Mandela University.

CapeNature initiates various noteworthy projects under the leadership of Dean Impson. Most of these are funded by the Table Mountain Fund or the WRC, and include:

- The effects of predatory alien fishes, with Jenny Day and her postgraduate students Darragh Woodford, Sean Marr, Dave Christie, Jem Shelton at UCT. This work results in improved understanding of the impact of rainbow trout (Woodford and Impson, 2004) and smallmouth bass (Woodford *et al*., 2005) on sensitive fynbos rivers and leads to a better awareness by the public in general, and anglers in particular, of the problems caused by alien fishes in our rivers. The impacts of predatory alien fishes on trophic structure in aquatic ecosystems, assessed by Dr Steven Lowe (Lowe *et al.*, 2005), has led to an improved understanding of the impact of alien fishes on aquatic macro-invertebrates and associated algal production.

- Genetic studies on Cape kurper (Heidi Roos), Cape Galaxias (Roelien van Niekerk) and redfins (Dr Ernst Swartz) leads to two MScs and one PhD at the University of Pretoria, several scientific papers and appreciation that the fynbos region is home to much more fish diversity and endemicity than previously realized. This is a collaborative study with Dr Paulette Bloomer and students from the University of Pretoria, Dr Skelton of SAIAB, CapeNature.
- River rehabilitation involving the eradication of alien fish in the Western Cape by means of a piscicide, rotenone. This project has gone through a substantial EIA and is due to be start early in 2012. The project involves detailed monitoring to quantify ecosystem response to the use of rotenone and the removal of alien fishes. This is a collaborative project between CapeNature, SAIAB and UCT.
- Identification of priority rivers for freshwater fish conservation in the Cape Floristic Region, as part of the CAPE biodiversity planning initiative. Further freshwater conservation planning work has been done by CSIR (Nel *et al.*, 2009) and the NFEPA Atlas has been finalized by SANBI and CSIR.

5.3 General

The technical meeting of the Ministerial Palmiet River Advisory Committee starts Paul Roberts – then Deputy Director General of DWAF – thinking about water requirements for estuaries. Paul Roberts is an example of someone who has authority and can influence both the scale of funding and the direction of research. Later, Henk van Vliet continues to play this role within DWAF, particularly in terms of his influence on WRC projects.

Will Alexander – Head of Scientific Services at DWAF – starts the first short-course training sessions on the use of simple hydrological models. He extends and popularizes the work of Professor Midgley and his students at Wits (especially Bill Pitman and Brian Middleton). Alexander also plays an important role in giving credibility to the Pongolo research within DWAF. Alan Conley at DWAF drove the production of 'The Red Book' – an overview of water resource availability, water use and projected water demands for South Africa (DWA, 1986). Midgley, Pitman and Middleton proceed to produce the first national overview of the hydrological features of South Africa (Midgley *et al*., 1994). The Red Book is followed in 1997 by an updated and highly summarized overview of the management of South Africa's water resources (Basson *et al.*, 1997). Subsequently, the WRC fund a review of the earlier publication on South Africa's water resources (Midgley *et al*., 1994), which results in an improved national overview with more reliable estimates (Middleton and Bailey, 2009). Another update of this important work has also just been launched by the WRC.

The DWAF 'Blue book' on water quality management in South Africa written by Wouter van der Merwe and Dirk Grobler (DWAF, 1989) explains the department's new approaches to water quality management, which are based on the receiving water quality objectives principles and the water's fitness for designated uses.

Mike Bruton moves from Director of the then J.L.B. Smith Institute for Ichthyology to take up the directorship of the Two Oceans Aquarium in Cape Town. His move precipitates an increased interest in making scientific information on fishes and aquatic ecosystems more easily accessible to the general public.

Research on the Modder River System continues and Nadene Slabbert obtains her Ph.D. under the supervision of Johan Grobbelaar on the possible impact of inter-basin transfers between the Caledon and Modder rivers. Another project conducted at this institute is the WRC-funded project on the genetic control of cyanobacterial toxins.

5.4 Institutional landscape

The period between 1994 and 1998 is one of fundamental change in the water sector. Minister Kader Asmal takes a strong lead in requiring the drafting of new national water legislation from first principles and national consultation rather than drawing primarily on public service capacity. He is open to involvement wider than the traditionally strong engineering approach to water resource management. The drafting teams responsible for the White Paper and the Act are highly representative of professions and sectors. This gives a strong boost for ecological research and Tally Palmer, the elected representative of SASAqS, is an important contributor to the development of the legislation.

Most operating divisions in the CSIR continue with dramatic transformation as the organization adopts a business-orientated culture and system of operations. As an example, the NIWR becomes Watertek in 1986. Watertek, Forestek, Ematek (earth, marine and atmospheric sciences) and Environmental Studies merge in 1995 to become Environmentek. Environmentek absorbed Miningtek in 2006 and becomes known as Natural Resources and the Environment (NRE). Later changes see the splitting off of the mining competence from NRE as a stand-alone entity.

5.4.1 Water Research Commission

The serious drought of 1966 combined with the ongoing and rapid industrial expansion leads the then State President C.R. (Blackie) Swart (on the advice of Mr Fanie Botha, the then Minister of Water Affairs) to appoint a Commission of Enquiry into Water Matters. The findings and recommendations of the Commission (CEWM, 1970) are accepted by the Government in 1970 (the report is printed verbatim in pages 1.13-1.61 of DWA, 1986). One of the specific recommendations of the Commission, in the light of projected water shortages in the long term, is the need to bolster the national research capability to improve the management of the scarce national water resource. The Water Research Commission (WRC) is established as a statutory body in terms of the Water Research Act (Act No. 34 of 1971), and starts operations that same year under the dynamic leadership of Dr Gerrie Stander who serves as both Chairman and Chief Executive Officer. Prior to his appointment as CEO of the WRC, Dr Stander led the NIWR's research on effluent treatment and water reclamation technologies in Pretoria. This work culminates in the full-scale Windhoek Water Reclamation Plant to supply potable water to the city of Windhoek in Namibia in 1968 – a world first. Dr Stander is followed in 1979 by Dr M Henzen who in turn is followed by Mr Piet Odendaal in 1985, both of whom had previously been NIWR staff members.

Following Piet Odendaal's retirement as Executive Director in 1999, Dr Rivka Kfir is appointed CEO in 2001. She restructures the organisation, and from the researchers' point of view, two changes are made which affect those being funded. The first is the consolidation of the research fields into four Key Strategic Areas that cover water resources, aquatic ecosystems, water use and waste management, and agriculture. The second is the introduction of the concept of solicited projects where the WRC Research Managers call for proposals to undertake specific targeted research.

Several important decisions are taken in the drafting of the Water Research Act (Act No. 34 of 1971) and the initial *modus operandi* of the WRC. The funding model is a levy on bulk water sales to water boards and government irrigation schemes. These funds are collected for the WRC by the Department of Water Affairs on a commission basis. This provides a predictable source of funds free from the budget cuts exercised by National Treasury during times of fiscal shortage.

Another important and far reaching decision is that the embryonic WRC would not establish itself as a research organisation with researchers and all the support needed, including laboratories. Flexibility is needed to address the range of research that the country needs and to be able to stimulate research in new topics as they arose. To achieve this, an early policy decision is taken to contract research out to existing organisations and to stimulate the establishment of new research establishments in cases where capacity to address problems is lacking. There are three specific advantages to this policy:

- Expensive research facilities need not be duplicated;
- The WRC will have no vested interests in establishing research needs and priorities and in funding research; and
- The WRC can maintain complete objectivity in the coordination and funding of research.

For the first three decades of its existence, the WRC organises research topics into research fields. As the need arises new fields are established and old fields are split, combined or phased out. In 1996 there are 17 active fields; some of these research fields are more active and longer-lived than others. In addition, during this period the WRC supports 2 centres, the Computing Centre for Water Research and the South African Water Information Centre, as support structures for researchers. It also supports two publications, *Water SA* which publishes scientific and technical papers, and the *SA Water Bulletin* which carries articles on current happenings, particularly on recently published WRC reports. During 2007 *Water SA* has an Impact Factor of 1.120, and is rated second amongst South Africa's ISI-rated journals and 17th amongst water journals worldwide. The *SA Water Bulletin* is superseded by the *Water Wheel* in the early 2000s and, written in a more readable style, this journal has become very popular across all branches of the Water Sector in South Africa.

The WRC mandate includes promoting co-ordination, co-operation and communication in water research and development; establishment of water research needs and priorities; stimulation and funding of water research according to priority; promotion of the effective transfer of information and technology and the enhancement of knowledge and capacity-building within the water sector. Execution of this mandate, supported by regular and predictable funding, contributes to putting South Africa in a leadership position in technology and policy over the years.

Some examples of ground-breaking technologies to which WRC funding contributes, include:

- Biological nutrient removal. A dry climate and the country's largest conurbation on the continental divide have led to severe eutrophication in the impoundments downstream of Gauteng and other urban centres. This makes nutrient removal during sewage treatment essential in South Africa. Biological nutrient removal is preferred because chemical methods lead to a build-up of salinity which is deleterious to downstream users. Starting in the 1960s at the CSIR's National Institute for Water

Research, with later phases funded by the WRC, various biological technologies are developed to remove nutrients, particularly phosphates, from sewage. While the designs are implemented, the capacity to operate these sophisticated plants remains an ongoing challenge.

- Water reclamation. During a time of severe drought and water shortages in Windhoek, Namibia, water reclamation was identified as the only short-term solution to augment the domestic water supply. Research on water reclamation had started at the CSIR's NIWR in the early 1960s and the NIWR-funded research led to the construction of the 4.5 Mℓ/d Stander Water Reclamation Plant at Pretoria's Daspoort sewage treatment facility in 1964, which tests a number of technological options for purifying domestic water to potable standards. This pilot scale Daspoort plant is the forerunner for the Windhoek Water Reclamation Plant in Namibia, which is inaugurated in 1968 and still supplies a significant percentage of the potable water used by the city of Windhoek. After its formation in 1971, the WRC contributes to funding some of the on-going water treatment and reclamation research that is being conducted by the NIWR at the Daspoort sewage treatment facility.
- Membrane technology. WRC-funded research develops technology that reduces the costs of seawater desalination using membranes. One of the major contributions to this is the development of novel membrane cleaning methods, which prolong the lives of the membranes.
- Dry cooling of power stations. WRC-funded research enables South Africa to implement dry cooling on certain large Eskom power plants, and these remain the largest dry-cooled power plants internationally.
- Inclusion of environmental water requirements into national policy and legislation. The WRC funded research on early studies to estimate the environmental water allocations for rivers and this contributes to the development of a sufficiently high level of understanding to enable the inclusion in the National Water Act (Act No. 36 of 1998) of the Basic Human Needs and Ecological components of the Reserve, ensuring the right of the environment to sufficient water to maintain the ecological services which deliver the benefits required of it by society.
- Development of the process of Strategic Adaptive Management (SAM), a method of identifying the desired state of an ecosystem with stakeholder participation through outlining the specific steps to be taken to achieve this in a way which is repeatable.
- The development of the Rhodes BioSure process whereby undesirably high sulphate concentrations (associated with, for example, acid mine drainage) are micro-biologically reduced to acceptable levels, using sewage sludge as the energy source for the microbes. The development of low-maintenance (passive) treatment technology for the treatment of acid mine drainage is also funded by the WRC.
- Regional gold mine closure strategy. Because in many cases it is the same reefs that are being mined, adjacent mines are often hydraulically interconnected. A WRC-funded project identifies the problems that this inter-connectivity of mines poses for closure planning and the apportionment of responsibility for water volumes and contaminant loads. They propose a set of procedures to address the various elements of a regional mine closure strategy, which are subsequently largely adopted by the regulating authorities.
- Computerised irrigation scheduling. Considerable improvements are made in agricultural water use through computerised irrigation scheduling.

The WRC celebrates its 40th Anniversary in 2011 by convening an important conference on the various water issues in South Africa and provides examples of some of the solutions to specific problems that the WRC has contributed to over the period of its existence.

5.4.2 Centre for Aquatic Research (CAR) at the University of Johannesburg (UJ)

By 2000, strong research programmes in ecotoxicology, parasitology and population genetics are established, and fish histology is added later with Ina Pieterse as project leader. Since 2005 fish ecology, including studies of fish stress caused by angling, is part of the programme in ecotoxicology with Nico Smit as project leader. A BSc Honours degree in Zoology (Aquatic Health) as well as MSc and PhD in Aquatic Health are introduced in 2000.

The department develops a branch of aquatic research into the field of freshwater, estuarine and marine ecotoxicology and establishes a niche in aquatic toxicology over the past 20 years. Research in the department now includes all disciplines of ecotoxicology, including toxicant identification and environmental distribution at different levels of biological organization from sub-cellular to ecosystem responses, to management implications through the ecological risk assessment paradigm. Training and services within the niche are represented as research-based MSc and PhD programmes and a tutored MSc programme. Accredited short courses in riverine and wetland ecology, management and rehabilitation are offered in conjunction with the UNESCO / Flemish Government / Water Research Commission in the funded FETWater programme. In an effort to increase the participation of other disciplines outside of ecotoxicology in the aquatic toxicology niche, the Centre for Aquatic Research (CAR) is formed in 2008. A number of changes take place in the aquatic science research processes in South Africa since 1995 and these are coupled with changing roles of the interdependent parties responsible for science policy, research and research management. Based on the collective experience gained through the current research focus and re-alignment with UJ's institutional objectives, the medium- to long-term objectives of CAR seek to make use of this memory and plough it back into the aquatic science research community in South Africa and neighbouring countries.

5.4.3 The Freshwater Research Unit (FRU) at the University of Cape Town

Freshwater ecological research is carried out intermittently in the Zoology Department at the University of Cape Town from the 1950s, when Arthur Harrison, Jack Elsworth and Marjorie Scott produce their important papers on the Berg River. Later, in the early 1960s, Graham Noble completes his PhD on mayflies and in the early 1980s Jackie King completes hers on the invertebrate assemblages of the Eerste River. At about this time Bryan Davies arrives as a Senior Lecturer from Rhodes University, while Jenny Day, a Lecturer in the Zoology Department, has become interested in the crustaceans in temporary pools. For the first time there is a nucleus of freshwater ecologists at the university.

The Freshwater Research Unit is established in 1984 with Bryan as Director until 1996, at which time Jenny takes over the running of the unit. Jackie King is not employed by UCT but is a contract researcher, and always has to find her own funding and – as she indicates rather sadly over the years – is considered by UCT to be very much a 'second-class citizen'. Despite due recognition not being given to her by UCT, Jackie teaches undergraduate students for many years, as well as supervising several MSc and PhD students and numerous Honours projects. She retires in 2009 but is still active in the field. Bryan retires in 2003, being replaced in 2006 by Cecile Reed, whose background is in parasitology and river health monitoring.

In the early years much of the funded research in the Unit is on the invertebrates of small local rivers, providing a sound basis for the understanding of riverine ecosystems and their biotas. Gradually research becomes more and more applied in nature. Jackie and her students begin to develop expertise in environmental water allocations. Jackie is now a leader in the field, being consulted about river management as far afield as south-east Asia, Pakistan and Ethiopia. Bryan works mainly on the effects of dams and inter-basin transfers of water on the river downstream. Jenny specializes in water quality issues, together with colleagues Helen Dallas and Heather Malan, both of whom are now actively involved in water quality management, Helen with regard to the effects of temperature on riverine organisms, and Heather with regard to water quality in wetlands. In various ways, Jenny, Helen and Heather are also involved in developing and using bioassessment techniques for monitoring aquatic ecosystems, particularly using components of the biota to assess water quality.

Over the last few years, FRU's expertise has expanded to cover wetlands and fish and – with the advent of Dr Muthama Muasya in the Botany department at UCT – macrophytes. Although the fish fauna of south-western Cape rivers is highly threatened, astonishingly little is known about their basic biology (diet, breeding requirements, time of spawning, etc.), or even about their distribution patterns. Postgraduate students in FRU are investigating these mysteries, as well as the effects of alien piscivorous fishes on the conservation of these threatened endemic fishes. Wetlands in the local area are also largely neglected but several WRC-funded projects have begun to change this.

The FRU is also involved in teaching limnology at undergraduate level, having started a third-year semester course on the ecology and management of South Africa's inland waters in 1996. For many students, of all their undergraduate courses, this is the one they appreciate most because it combines 'real science' with practical management issues and they feel that it gives them a peek into the world beyond university. Unfortunately, 'rationalization' is about to hit this course – it is run for the last time in 2011.

Because fresh water and aquatic ecosystems are of such great importance, there is huge demand for freshwater ecologists, but seldom for long-term contracts. As a result, the graduates of FRU form consulting firms, allowing them to practise their discipline, to earn a salary, and to contribute to contribute to the management and conservation of our aquatic ecosystems. Southern Waters, run by Cate Brown, deals mostly with river management; the Freshwater Consulting Group, jointly run by Geordie Ractliffe, Liz Day, Dean Ollis, Justine Ewart-Smith and Kate Snaddon, deals mostly with urban ecosystems and wetlands; DHI Consulting, run by Bill Harding, deals mostly with the management of lakes and reservoirs.

5.4.4 University of the Free State

Aquatic sciences research at the then University of the Orange Free State, now the University of the Free State, continues uninterrupted since its beginnings in the 1960s when Willem Scott, Ferdie Schoeman and Pieter Keulder carry out studies on *in vitro* algal bioassays for their masters degrees.

In the early 1970s, Ferdie Schoeman studies the diatoms of Lesotho for his PhD. Eduard van Zinderen Bakker (see **Section 1.5.4**) sets up a large multi-disciplinary study on the limnology of the then Hendrik Verwoerd Dam (now called the Gariep Dam). Prominent participants in this programme are Peter Stegmann and Johan Grobbelaar who work on water quality and phytoplankton, Pieter Keulder who studies the chemistry of suspensoids, Dawie Kok who works on zooplankton, and Kas Hamman who studies the fish population. Peter Ashton, then at Rhodes University, is also part of the overall study, working on the autecology of the red water fern, *Azolla filiculoides*.

During the late 1970s, Daan Toerien takes over the leadership of aquatic ecology studies at the university and, with Johan Grobbelaar, helps to start the CSP programme on the ecology of turbid waters using Wuras Dam as a case study. At this time, Braam Pieterse co-ordinates a new post-graduate programme in limnology, which accepts its first class of honours students in 1980. Danny Walmsley works on a large project for the production of pharmaceutical products for the firm Sentrachem, while Johan Grobbelaar works on a parallel project on the mass culture of algae. Kobus Eloff studies ways to mass culture the toxic cyanobacterium *Microcystis* and also works on the toxicity of this species. The Institute for Groundwater Studies comes into being and now has an international reputation for its excellent contract work and teaching.

From the 1980s onward, Maitland Seaman and Dawie Kok work on the ecology of temporary waters, with collaboration from Luc Brendonck of the Royal Museum of Brussels and later the Catholic University of Leeuwen. Later, from 2005 onward, excellent work is carried out by Bram van Schoenwinkel of Leeuwen on the ecology of temporary rock pools.

During the early 2000s, a large multidisciplinary team from the UFS, Rhodes, UCT and the CSIR, funded by the WRC and led by Maitland Seaman, with Jackie King as advisor, develop a methodology for the assessment of environmental water requirements for non-perennial rivers.

In 2008, the UFS establishes a Strategic Academic Cluster, one of six, 'Water management for water scarce areas', with Maitland Seaman as full-time Director. The Cluster will coordinate and promote the focus areas related to aquatic ecology, conservation of water, climate change and socio-economic development. Attached to the Cluster are various postgraduate courses with aquatic ecological components.

5.4.5 The CSIR's Natural Resources and the Environment unit

Arising from the several transformations that took place within the CSIR, the Natural Resources and the Environment business unit continues to conduct research and consultancy projects across the Water Sector. Despite the reduction in numbers of staff who work on different fields within the aquatic sciences, the unit continues to publish research articles and reviews in addition to the numerous contract reports for external clients.

Emphasis is placed on catchment-wide studies – such as those conducted in the Olifants River catchment – to understand the many inter-linked sources of contamination from agriculture, mining, industrial and domestic effluent discharges that contribute to widespread and progressively worsening water quality (*e.g.* Ashton, 2010; Oberholster *et al.*, 2010). Other areas of focus include: human health aspects associated with contaminated water sources (*e.g.* du Preez *et al.*, 2011), water use by plants in different vegetation types (*e.g.* Everson *et al.*, 2011), impacts of alien vegetation on water quality and water use (*e.g.* Le Maitre *et al.*, 2011), governance systems associated with the management of water (*e.g.* Funke and Jacobs, 2011), risk assessment of nanotechnology applications to aquatic ecosystems (*e.g.* Musee *et al.*, 2010; Musee, 2011), acidic mine drainage in the Witwatersrand basins (*e.g.* Madzivire *et al.*, 2011), groundwater dependent ecosystems (*e.g.* O'Farrell *et al.*, 2010) and systematic conservation planning processes for the delineation of priority freshwater ecosystems that deserve protection (*e.g.* Roux *et al.*, 2008; Nel *et al.*, 2011b).

The increased public attention given to water shortages in particular areas, acid mine drainage, inadequate delivery of water services to urban and rural communities, increasing incidents of water pollution, and poor water resource management set the tone for the NRE's research agenda in future years.

5.4.6 The Department of Water Affairs' Directorate Resource Quality Services

Around the time of the establishment of the WRC, a Department of Water Affairs scientist by the name of Joan S. Whitmore is agitating for the establishment of a separate institute within the Department that would be dedicated to hydrological research. After strenuous lobbying, she persuades the DWA managers to construct the Hydrological Research Institute at Roodeplaat Dam, as described in detail in **Appendix B**. Joan Whitmore becomes the first director – an unusually senior civil service appointment for a woman at that time – and sets about staffing and equipping the HRI.

By the end of the 1970s, the importance of having not only sufficient volumes of water but adequate quality had become clear. Under the leadership of Henk van Vliet and with the technical skills of people such as Izak Schoonraad and Bets Davies, the HRI develops an innovative automated inorganic chemistry laboratory using auto-analysers and an in-house laboratory information management system running on a Varian computer. The new laboratory greatly increases the throughput of water quality samples and caters for an expanded monitoring network. Around this time, Phillip Kempster implements a trace element measurement system using an inductively coupled plasma unit. By the mid-1990s, water quality is the key function of the institute, which becomes known as the Institute for Water Quality Studies.

Another aspect of the management of water quality is the observation and modelling of catchment processes, and Alison Howman pioneers work in the use of remote sensing to monitor land use changes and eutrophication during the 1980s. The HRI acquires image processing hardware and software and starts a small remote sensing group which later broadens into geographical information systems in general. The reporting of water quality in its spatial context is now much simpler with the appearance of web-based applications and in 2005 Mike Silberbauer prepares the first spatial inventory in Google Earth™ of the thousands of DWA water quality monitoring sites.

Following the change in emphasis from water quality to water quantity, the next shift in priorities is measuring habitat integrity, as described elsewhere under the River Health Programme. This begins under Henk van Vliet's directorship and continues with his successor, Mbangiseni Nepfumbada. Early in the 2000s, during a widespread restructuring of DWA, the IWQS changes its name again and becomes Resource Quality Services, to reflect its broader (national) monitoring responsibilities. The directorate is now responsible for national monitoring of chemistry, eutrophication, aquatic ecosystems and microbiology, with some involvement in radioactivity, toxicity and estuaries.

The institute has always served as a training ground for scientists and technicians of all specialities, and Joan Whitmore lamented the poaching of her first scientists soon after the Institute opened. In spatial analytics alone, RQS has supplied South Africa, Australia, New Zealand and Germany with 17 experienced scientists.

Other institute directors not mentioned above were Willie Hattingh, Eberhard Braune, Quentin Espey and Nadene Slabbert.

5.4.7 The digital revolution

It may be difficult for young scientists to imagine that as late as the early 1990s, scientists would write manuscripts by hand and then give their notes to a typist for typing. A pool of typists was part and parcel of every scientific organisation. The advent of personal computers, the Internet and e-mail, cellular phones and digital cameras mark a complete workplace revolution. Every person becomes the author of their own digital content, capable of manipulating and sharing text in ways that were not previously possible. This capability, together with instant access to almost unlimited amounts of information, contribute significantly to efficiency and productivity – but perhaps at the cost of a chronic danger of overload and lack of proper archiving.

Up to the middle 1990s, it was common to plan a field trip with the aid of 1:50 000 topographical maps. The availability of GPS instruments and Google Earth has changed much of that. During this era, many analytical detection limits are also significantly improved as advances in analytical instruments have been made. In some cases, this results in authorities lowering the concentrations of specific water quality constituents that are allowed in water designated for particular uses.

5.4.8 Field work

From the mid-1990s, the increasing threats of vandalism and hi-jacking plus growing risks to personal security becomes an increasing disincentive to undertake fieldwork – especially in remote areas. This contributes to the development of a new generation of 'desktop ecologists' who are prepared simply to work with the data collected by others or generated by models (so-called 'pure data'" – simulated or modelled data that are untouched by human hands).

In 2007, Peter Ashton and Dirk Roux successfully motivate to CSIR management to take a group consisting of a few experienced field ecologists and approximately 10 young aquatic scientists – who had little or no previous experience of field work – on a short field excursion to the Kruger National Park. The three-day excursion is accompanied by Andrew Deacon of SANParks who provides a wealth of insights into the rivers running through the KNP. All of the young researchers feel that the excursion had re-ignited an excitement about science and that the trip is a prime opportunity for knowledge sharing, across disciplines and between experienced and inexperienced researchers. Every participant concludes that the first-hand observation and study of ecological processes provides important insights and valuable experience that cannot be gained from working with a model, studying a textbook, undertaking coursework, or any combination of these.

While academics from some universities experience a decline in student interest to undertake field work, some institutions (notably the University of Johannesburg and North West University) place more emphasis on fieldwork now than they did in the past. Field work remains an important and intrinsic part of most undergraduate courses at UCT.

5.4.9 Capacity issues

Following the promulgation of the new Water Services Act in 1996 (Act No. 108 of 1997), Fred van Zyl moves to the Directorate Water Services and much of the impetus for water quality management within DWAF is lost. At around the same time, Martin van Veelen, Andrew Brown and Andrew Bath also leave DWAF to join local consultancy firms, further depleting the available water quality management skills within the Department.

In a number of critical fields, especially those that are not directly orientated towards resource management, South Africa literally has very little or no capacity left; for example, in sediment transport modelling, water quality modelling, resource economics (costing ecosystem services) and reservoir research. In order to conduct a comprehensive estuarine reserve estimate, one has to draw in every qualified estuarine scientist in the country. In a recent review of fish research in South African estuaries (Whitfield, 2010), Allan Whitfield points out that the number of experienced ichthyologists working in South African estuaries has declined over the past two to three decades. As an example, of the 12 major role players who featured in a related but earlier review (Whitfield, 1996), only two senior scientists are still actively engaged in estuarine fish research (and both these will retire before 2020). Of the other 10, two are now deceased, one has retired, three have joined the private sector or become managers, and four have emigrated to Australia and New Zealand (Whitfield, 2010).

For science to make its potential contribution to society in a time of extreme urgency you want and need the very best of the skills in the student body. However, a fairly general perception among academics is that capable post-graduate students quickly become consultants or are hired by government departments for non-scientific jobs and hardly anyone remains active in full-time scientific research. Some feel that this is because there are no good, well-paid research jobs available. Many of the current students seem to want a degree so that they can get a management job; they seem to lack the enthusiasm and commitment that is needed to undertake good research and build a career in research. Jay O'Keeffe commented that he is not seeing the exciting student experience from UNESCO anywhere in South Africa.

South Africa urgently needs a strong and growing cadre of passionate and competent black scientists. Currently, science is not a preferred pathway for many young people seeking a career. A research career does not always have a clear identity, is perceived to require too much patient persistence, and entails hard work – often at low rates of pay. The civil service does not offer an attractive career prospect for young scientists who ultimately have to rely on experienced specialist mentors for their own career development.

Several academics with senior management responsibilities have expressed the feeling that "*I can't wait until I retire so that I can start discovering again*." A few younger scientists who have attended regional workshops indicate that it is difficult for them to identify with a 'noble purpose' of science because they seem to be forever fighting to secure the next short-term consulting project if they want to retain their jobs.

The WRC Steering Committees provide important connectivity and a vibrant review environment in the early 1990s. However, nowadays, it seems to be increasingly common that members of the Steering Committees (or Reference Groups as they are now more commonly known) are unable to attend the meetings (usually because of time and cost constraints in their parent institutions). Naturally, there are many exceptions to this generalization, but capacity constraints caused by a shortage of experienced staff seem to pose a challenge to the effectiveness of these meetings.

6 CONSOLIDATING PERSPECTIVES

6.1 General trends over time

6.1.1 The early years (1900-1945)

During the early years, only a handful of aquatic researchers practise their trade in South Africa. Most, if not all, of these remarkable men and women are educated overseas, for example, Mary Pocock, Keppel Barnard, Evelyn Hutchinson and John Day are educated overseas. They were all pioneers and innovators, finding the ways and means to conduct their research with very little support in terms of instrumentation, facilities and finances. The one resource that they had was time, and almost complete freedom to carry out research on topics of their own choice.

Fieldwork is central to any research initiative, with the collection and description of new species making up a significant part of 'scientific discovery' during this era. Researchers find inspiration and guidance from the work of their international peers. Interestingly, as demonstrated by the research of Professor Duerden on ostrich husbandry and later wool production, early workers are not averse to conducting applied research.

In contrast to countries such as the UK, Canada and Australia, where science councils are established to promote organised research in support of technological development, South Africa appears to have largely lacked any national coordinating mechanism or vision for science during this era.

6.1.2 The middle years (1946-1979)

The middle years brought organisational structure to the science enterprise in South Africa, with the newly established CSIR playing a pivotal role in this regard. Related developments include the establishment of the Limnological Society of Southern Africa (1963), Institute for Freshwater Studies (1964), J.L.B. Smith Institute for Ichthyology (1968), Water Research Commission (1971) and the Hydrological Research Institute (1972). Important research programmes were started during this era, notably the National Programme for Environmental Sciences in 1972 and the Co-operative Scientific Programmes in 1975. South Africa's first Water Act (1956) and the publication of a very influential report by the Commission of Enquiry into Water Matters (1970) provide national direction.

A growing appreciation for the inherent connectedness of biophysical systems and acceptance of the concept of ecosystems spawn a global initiative, the International Biological Programme (IBP), to coordinate large-scale ecological and environmental studies. South Africa responds to this international movement by establishing the National Programme for Environmental Sciences (NPES). This is a very significant event in the chronology of aquatic science because it provides, for the first time, a national vision that is to become a rallying point around which researchers can build learning relationships. The era of the national programmes is characterised by collaboration across the country while individual researchers and groups are encouraged to become internationally competitive. It is noteworthy that at the start of the NPES there is a predominance of young scientists who had yet to gain the confidence that would be required to compete internationally. The administrators give considerable attention and support to profiling the researchers and research conducted under the banner of the NPES. This ranges from simple things like having lunch once a year with the President of the CSIR, to supporting participation in national and international conferences, and encouraging researchers to join the specialist working groups set up by the International Society of Theoretical and Applied Limnology

(SIL) and the UN Scientific Committee on Problems of the Environment (SCOPE). The administrators have a long-term vision and embark on a deliberate strategy of constructing the profile of researchers and research so that as the NPES grows to a close researchers are confident in their capabilities and have achieved recognition abroad. With this confidence they are able to contribute to the organization of the First International Conference on African Limnology held in Nairobi in 1979 and later, in 1984, to host the Conference on Southern Hemisphere Limnology. The contribution of the NPES to the national competency in aquatic research and management deserves special recognition.

The period of the Co-operative Scientific Programmes (CSP) stands out as a period of relatively high cohesion among aquatic scientists in the country. The depth and breadth of scientific research that results from these programmes is unequalled to today. This positive influence on aquatic science is reflected in the meetings of LSSA, where people are excited to hear progress from others because they feel that they are all contributing to something bigger and that their work has real relevance.

A number of field stations are established around the country – Lake Sibaya field station (1967), Gariep Dam research laboratory (1973), Swartvlei research station (1974) and Pongola Floodplain research station (1974) – which provide excellent facilities for academic supervisors to take students into the field and expose them to the realities of specific aquatic systems. These practical extensions of the lecture hall make a significant difference in the training and enthusiasm of students and often provide the fuel for passion and getting students 'hooked' on a career in science. Socialisation between students and academics in the field is a prime opportunity for knowledge sharing, especially for students and inexperienced staff members.

During this era, South Africa continues to attract researchers from overseas including E. M. van Zinderen Bakker (Netherlands), Bryan Davies (University of Newcastle via the University of Maputo); Jay O'Keeffe (University of London); Richard Robarts (University of Waterloo, Canada), Tamar Zohary (Hebrew University of Jerusalem), Alan Ramm (United States), and Andrew Jarvis (United Kingdom).

6.1.3 The turbulent transitional years (1980-1994)

During this period, Rhodes University initiates a Masters Degree in Limnology (1980) and the University of the Free State starts an Honours Degree in Limnology (1983). The Freshwater Research Unit is established at the University of Cape Town (1984) and the Institute for Water Research at Rhodes University is formed (1991) by merging the Institute for Freshwater Studies and the Hydrological Research Unit. The Hartbeespoort Dam Ecosystem Programme (1980-1989) is a certain research highlight.

External pressures such as the drive to commercialise research and a certain degree of international isolation, together with the internal demise of the Co-operative Research Programmes, has a profound effect on the course of aquatic science in South Africa. In a sense, the 1980s spell the end of what many consider to have been the 'golden era' of aquatic research in South Africa, and it would take some time for a new order to emerge. This transitional period is characterised by a number of 'post-CSP' trends:

- During the period when the CSPs were operating, the way in which studies were conceptualised required people to do a lot of fieldwork. Financial constraints associated with the commercialisation of science have the result that fieldwork was viewed as a high cost and, increasingly, the reduced project budgets cannot afford to carry out sufficient, if any, fieldwork. Studies nowadays are commonly designed to require less fieldwork and focus more on desktop work. This may have to do with the change in the nature of research projects and the types of answers required by water resource managers, more than an unwillingness of researchers to go to the field. Furthermore, at least some of the fieldwork that took a week to complete in the days of the studies at Lake Sibaya can now be done ‘instantly’ with an instrument. The downside of this is that scientists become removed from the systems that they are studying, and lose the ability to gain a deeper understanding of their systems and to make intuitive deductions based on careful observation.

- During the period when CSP operated, there was a national vision for science; now it seems that every organisation has to have its own vision (*e.g.* WRC, CSIR, etc.) and the vision for aquatic science as a whole seems to have dimmed close to the point of extinction. The time of the CSP is marked by research funders (FRD) that work hard to profile South African research on the international stage and to themselves work at building relationships with acknowledged researchers. They create and sustain a platform on which the researchers can interact with each other and ply their trade. With the commercialisation of science, human resources performance evaluation tools start to encourage research administrators to measure themselves less against the advancement of science than against financial targets and organisational or short-term political objectives.

- Heads of university schools or departments now receive many more administrative responsibilities and seem to have lost most of their decision-making autonomy, power, authority and scientific influence. In several instances, the heads of larger units or departments used to be internationally-recognized leaders in science; the growing administrative demands now result in at least some of these leadership positions being taken on by full-time administrators or managers.

- It appears that support for careful, time-consuming PhD-type research has diminished after the CSP years, and contract research has risen as an alternative. Many scientists have become consultants to put bread on the table, and to be involved in their discipline in the absence of ‘real science’ jobs out there.

A positive memory of this period is the strong sense of cohesion amongst aquatic scientists across organisational boundaries as well as a synergistic relationship between aquatic scientists and a highly competent and motivated group of water resource managers (mostly engineers) from DWAF. A second positive note is the important role that the WRC starts, and continues, to play in facilitating knowledge production, sharing and management in the water sector.

6.1.4 The latter years – adapting to change (1995-2010)

Comprehensive revision of South Africa’s water legislation dominates the aquatic science scene during the early part of this period. The White Paper on a National Water Policy is accepted by Cabinet in 1997, and is followed by the publication of the National Water Act (Act No. 36 of 1998) and the National Water Resource Strategy in 2004 (DWAF, 2004).

Pervasive restructuring and name changes characterize the institutional landscape during this era, for example the J.L.B. Smith Institute for Ichthyology becomes the South African Institute for Aquatic Biodiversity in 1999; the Hydrological Research Institute is renamed as the Institute for Water Quality Studies in 1994, which in turn becomes Resource Quality Services in 2003; and CSIR’s National Institute for Water Research becomes Watertek in 1986, which then morphs with two other units into Environmentek in 1995, which in turn becomes Natural Resources and the Environment in 2006. Adding to changes at the organisational front, the Centre for Aquatic Toxicology is established as part of Rhodes University's Institute for Water Research in 1999 and the Centre for Aquatic Research is formed at University of Johannesburg in 2008.

From the middle 1990s, the River Health Programme enables the collection of data that show, through State-of-River reports, the relatively poor state and ecological integrity of many South African River systems. This undesirable state of affairs is confirmed when South Africa's first National Spatial Biodiversity Assessment, conducted in 2004, finds that the country's river systems are more threatened than terrestrial or marine ecosystems.

Whereas the scientific enterprise has until the 1980s been largely autonomous and governed itself based on its own normative benchmarks and standards, science now finds itself operating within a much more rigid set of hierarchical structures and bureaucratic management approaches. With these changes emerged more administrative responsibilities and a need to account at an ever-shrinking time frame (*e.g.* more regular progress reports). It must be stated that at least a part of this 'cultural revolution' within scientific practice reflects a global phenomenon. To this end, John Ziman, who was an accomplished physicist and outstanding spokesman for science, wrote: "*As scientists we experience a time of turmoil in our profession and science is under pressure to abandon many of its cherished customs. We need to think hard about what is happening and how we should respond, not only to survive but to responsibly serve humanity*" (Ziman, 1996).

The national custodian of water resources (currently the Department of Water Affairs) is, amidst endless transformations and chronic capacity constraints, in a process of delegating many of its responsibilities to more local-level Catchment Management Agencies. Eroded institutional memory caused by the loss of experienced staff members has weakened the national capacity to use all the information that has been so proudly produced as highlighted in previous sections of this report.

It seems that the current reality is that too many aquatic ecosystems are in a poor ecological state, the research teams experience some internal turmoil and the government department responsible for water resources management lacks sufficient capacity in terms of the technical experience and skills required for this complex job. How can the water enterprise regain a strategic national vision, make aquatic research a desirable profession, and recreate a dedicated and highly competent steward?

Kevin Rogers and others propose strategic adaptive management as a means to plan, learn and adapt together as researchers, managers, and all relevant stakeholders. Because water resources are essentially embedded in social systems, which are typified by a range of stakeholders with wide ranging expectations and values, the socio-ecological issues that need to be addressed are associated with substantial uncertainty and high decision stakes, and require close collaboration with non-scientist stakeholders (Rogers, 2006). To this end, post-normal science (Rogers, 2008) and trans-disciplinary research (Roux *et al*., 2010) have been proposed as new-era ways to respond to the challenges faced by the aquatic research and management institution in South Africa.

7 CONCLUSIONS AND RECOMMENDATIONS

7.1 Conclusions

"*We think of life as a story and wish it to end well*", (Kahneman, 2011).

This quotation from Kahneman (2011) exemplifies a sentiment that is held by most individuals, but one that is seldom spoken about. We all share the aspiration that our lives should be interesting, fulfilling and rewarding; the same sentiment applies to our careers. As aquatic scientists engaged in research, we all want to tackle interesting problems, help to grow the cadre of scientists, broaden and deepen the understanding and application of our science, and help to make a positive difference to society. Similarly, we all aspire to the feeling that our careers have contributed to the well-being of society and that our efforts have not been in vain. Unfortunately, the current reality is that there are too few career opportunities available for the number of aquatic scientists who are interested in research, while there is a simultaneous, diminished capacity within water resource management institutions to take up and apply research findings.

South Africa is not alone in this situation, as illustrated by a quotation from the preface of the third edition of Robert Wetzel's book on limnology: "*Limnology is currently experiencing a period of introspection. Such criticism is healthy if done constructively and the causes of underlying deficiencies are recognized and addressed. Many problems have arisen, however, in part because of the purported necessity to respond rapidly to governmental and societal demands without an in-depth scientific underpinning. A root cause is our continuing inability to properly educate and train students and the public. Society must recognize that intellectual creativity is essential to excellence in science and that excellence in science is essential to the most effective and cost-efficient management of our resources*" (Wetzel, 2003).

This eloquent summary (Wetzel, 2003) highlights the fact that the problems we face are the same as those faced elsewhere in the world. However, this should be no reason for complacency or comfort on our part. South Africa faces a future where escalating demands for water are not matched by the supplies that are available, and the integrity of these supplies continues to be compromised by widespread pollution and the impending threats posed by global climate changes. Put simply, if we do not put in place cost-effective and sustainable solutions to the water quantity and water quality problems we face then we will experience escalating problems of social unrest.

Given the poor spatial and temporal distribution of our water supplies, plus our absolute dependence on water storage reservoirs to supply water during the dry months of the year, it seems inconceivable that we should not deploy the best skills available in engineering and aquatic sciences to develop the long-term solutions that are needed. Unfortunately, it appears that the urgency of these issues is not widely understood and we do not see sufficient efforts directed to strengthening the national cadre of aquatic science and engineering. In particular, efforts that are directed towards solving pressing problems linked to water supply and water pollution appear to be proceeding at a snail's pace.

Our study revealed an unfortunate feature in terms of the progressive decline in the extent and integrity of national water quantity and water quality monitoring systems. There is clear evidence that, from a water quality perspective, for example, fewer sites are being monitored, fewer variables are being analyzed and the frequency of sample collection is declining. Given the progressive and widespread decline in water quality across South Africa, the reduction of monitoring efforts will hamper the effective management of our country's water resources.

On the principle that 'if a resource is not measured then it cannot be managed', there is a clear and urgent need to expand and improve our monitoring efforts and not to reduce them.

During the preparation of this report we repeatedly saw the importance of the need for at least some degree of institutional stability, where people stay in the system long enough to develop a sense of shared responsibility and proud ownership of outcomes. Importantly, institutional or organisational memory is based not only on explicit information in reports and data systems, but also on the tacit knowledge that resides in people and their inter-relationships. Those tacit and explicit elements have shaped, and will continue to shape, aquatic science in South Africa. If we simply 'eject' experienced aquatic scientists from our institutions, for whatever reason, we lose an enormous 'bank' of knowledge and insight that can still be usefully deployed.

There is clearly a need for an improved, broader, national vision to guide the development and deployment of aquatic science in South Africa, so that aquatic scientists can continue to contribute to the sustainable management of the country's water resource base.

A large number of aquatic scientists were trained in South Africa during the period 1965 to 2005 so that, overall, there are now a greater number of these individuals than was the case in earlier years. However, the number of aquatic scientists that conduct active research in South Africa is in decline and the post-1994 period has not delivered sufficient new talent to meet the needs of a country where "*Limnology, as the science which, with hydrology, underpins effective water resource management, should be amongst the most carefully nurtured of all South African scientific enterprises*" (Williams, 1989). This is partly a reflection of a global decline in the field of limnology (Wetzel, 2003) and, more importantly, a consequence of the failure of the South African education system at all levels to educate a new generation of scientists (Cherry, 2010). The same argument holds for engineers, without whose expertise most water management schemes would be impossible.

A part of the problem behind the decline in numbers of active aquatic science researchers relates to the diminishing number of aquatic science research positions that are available at South African universities and research institutions. Thus, despite the larger numbers of trained aquatic scientists, most of these individuals have had to choose employment opportunities – for example, as environmental consultants – that offer little in the way of research opportunities. In some instances, this move towards consulting as a profession has impeded open interactions and communication between individuals working for different firms because of concerns about the value of particular types of information or data and possible competition for the limited research funding that is available. Another consequence of the need to work as a consultant is that individuals tend to move between firms more frequently, experiencing less continuity of work in terms of building a career in research or in multi-disciplinary programmes, and this is accompanied by a decrease in the collective institutional memory.

Most people seem to have too little time available. The majority of active aquatic scientists that we approached during this study, and especially those in senior positions, expressed their keenness to participate in the chronology project. However, few could find the time to do so. We were alarmed by how 'tied up' most people are in dealing with their existing commitments and administrative responsibilities. This begged the question: in such a crowded work-life, how much space is left for reflection, creativity and originality?

Our impression is that the original strong focus on excellence in science is waning. Many participants referred to how scientific excellence was the only criterion that mattered for the outstanding individuals of the past. We feel that the current efficiency drive to do more 'things' in less time is eroding a great deal of the excellence mentality that characterized aquatic science in the early and middle years of the last century.

There appears to be a high degree of confusion entering the ranks of aquatic scientists. Several members of the younger generation of scientists indicate that they find the job description of an aquatic scientist to be unclear. It has certainly changed from what it used to be prior to 1980. Are we supposed to be scientific researchers or consultants? It seems that the boundary between these two activities has become almost completely blurred. Jane Lubschenco noted that, as researchers, "*we relish the fun and challenges of problem-solving, and we wish to contribute something useful to current and future generations*" (Lubschenco, 1998). During our interactions with aquatic scientists across the country, we did not see much evidence of this outlook amongst our aquatic scientists – to us, it seemed to be more a case of people having to 'hang in there' to survive.

It is here that the need for strong, decisive scientific leaders is perhaps most clearly evident. By leaders, we mean individuals who have extensive experience in one or more fields of aquatic science, who have established an international reputation for their work, who have a passion for accuracy, precision and attention to detail, and to whom 'excellence' is the hallmark of everything that they undertake. Strong leaders have an almost uncanny ability to bring together teams of like-minded individuals whose passion for their work drives them to succeed, and who are driven by their desire to excel. In an era of reduced and indeed diminishing sources of funding for research, the ability of strong leaders to assemble teams of outstanding individuals and guide their collective energies towards a shared goal enables them to attract sufficient financial support for their endeavours.

Here, it is important to distinguish between 'leaders' and 'managers', whose main function is to oversee and guide the administrative aspects of research programmes, to 'create the space' needed by good leaders and their teams. Far too often, it seems that institutions regard 'good managers' to be the same individuals as 'good leaders'; in reality, this happy state of affairs is seldom true. Unfortunately, when the leadership and management roles are combined and the individual concerned lacks the appropriate blend of expertise and experience plus adequate support, their efforts to lead and manage become diluted and they seldom fulfil their potential.

The important function that SASAqS used to fulfil in bringing together water resource managers and aquatic scientists from all disciplines needs to be revitalized. This would help to re-establish and strengthen the previously strong links between aquatic scientists and those individuals in Government who are responsible for water resource management and policy. In turn, this would enable aquatic scientists to more clearly understand the specific information needs of water resource managers and also to help them to transfer research findings to water research managers.

Many improvements have taken place during the past century in aspects such as monitoring apparatus, mapping ability, navigation and data processing. Occupational health and safety, though sometimes frustratingly bureaucratic in comparison with the more easy-going ways of the past, have improved beyond all recognition and are very important as some of the hair-raising anecdotes in this document attest. Yet we sometimes yearn for a, possibly imaginary, simpler era. Scientists who built their own instruments understood their limitations better and were less likely to overestimate their reliability. Camping out on a floodplain with the gentle grunting of hippos and the occasional reflection of crocodile eyes in the torchlight were more likely to impress upon the young limnologist where his or her position was in the greater scheme of things – not to mention the food chain – than the striking but remote picture from a Google Earth® image or StreetView®.

7.2 Recommendations

Based on our findings in this study and the conclusions that we have drawn, we make the following recommendations.

There is a clear and urgent need to strengthen the South African education system at all levels so that it provides an environment within which the individuals that have the ability and drive to develop a career in science and / or engineering can flourish. Equally problematic is the need to create sufficient opportunities for aquatic scientists and engineers to develop meaningful careers and help to achieve the goals articulated in our national vision for water resources. A key part of the career development of all individuals is the crucial role played by experienced mentors who can guide less experienced colleagues to develop their careers. At the same time, the education system needs to develop technically-skilled individuals who are capable of developing, adapting, manufacturing and maintaining the instrumentation and software that are pivotal to the scientific enterprise.

Equally importantly, aquatic scientists must appreciate the need to deploy their skills and experience to address those societal needs that relate to their fields of expertise. It is no longer possible for an aquatic scientist simply to undertake research on an esoteric matter of personal interest that may have little or no relevance to broader society. This will require aquatic scientists to move beyond the ‘traditional’ simple production of a ‘set of results’, and instead make sure that their results can be turned into ‘solutions’ that will help to solve a particular problem experienced by society.

The national systems of water quantity and water quality monitoring urgently need to be expanded and improved to the point where they can provide reliable data to aquatic scientists and engineers. These data form the foundation upon which defensible decisions can be made on the sustainable management of our water resources.

There is now a growing realization that rivers and the water they transfer connect our people and economies across local and international boundaries. We cannot pretend that South Africa can somehow isolate itself from the rest of the region. Because of our economy, experience and competencies, we also have a broader responsibility to develop the regional understanding and competencies that are required to make the inevitable trade-offs in ways that are equitable and sustainable. Ideally, the WRC should continue to be pivotal in developing and sustaining the partnerships that are needed to enable research to take a regional, social-ecological systems perspective of the management of water resources.

As we have come to appreciate the need to understand socio-ecological systems at landscape, continental and global levels, and as we have come to appreciate the need to acknowledge and engage complexity, it is increasingly clear that we need to 'return' to a more programmatic approach to research. As the scale of investigation increases to landscape-level studies focussed on complex social-ecological systems, the issues of concern are often too broad and too complex to be addressed by a single project. To deal with such issues would require the integration and synthesis of insights and findings from a number of research projects covering multiple disciplines (**Figure 4**). Component projects may run in parallel or may need to run sequentially. A dynamic portfolio of inter-dependent research projects can be conceptualized as a research programme. However, the programme is not just a collection of related projects, but a stated intention to strive for a desired common goal that will not be reached simply by summing the tangible products of the component projects (Charles Breen and Associates, 2011).

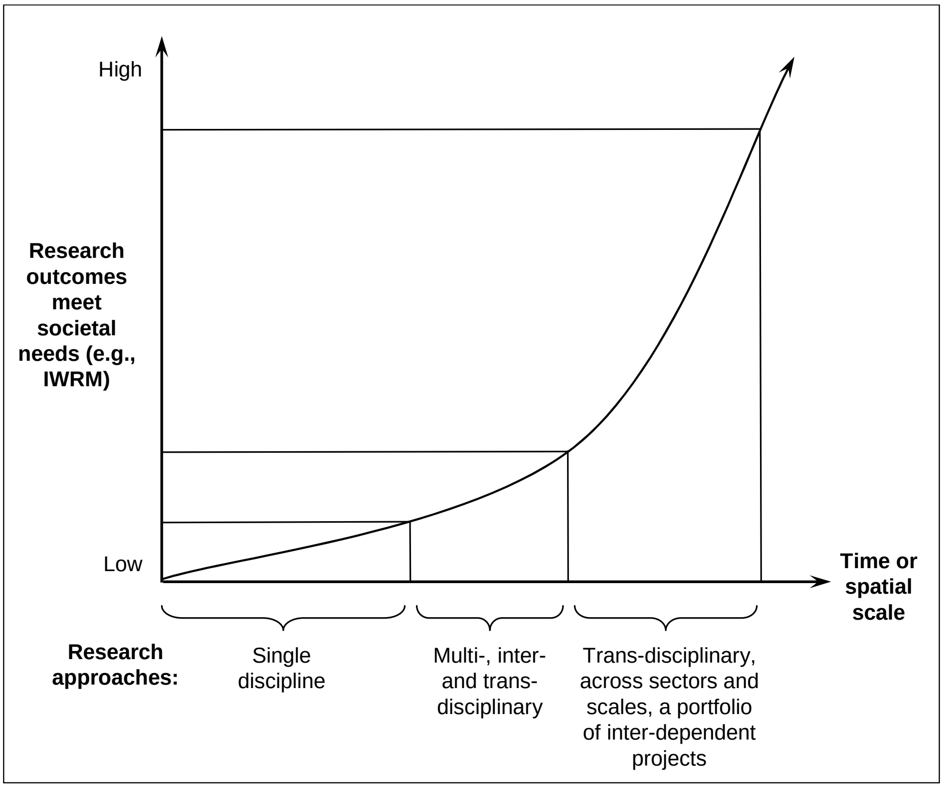


Figure 4. Schematic diagram to illustrate the improvement that can be achieved in terms of research outcomes that meet society's needs when greater integration and synthesis of research efforts occurs. (Diagram adapted from Palmer, 2010).

Research programmes seek to produce new knowledge, new alliances and new understanding that will influence the longer term management and governance of the use of a particular resource. Effective research programmes require us to build knowledge systems that span disciplinary, research, policy, and operational domains; this takes much more time and requires more persistence and investment in social capital than is typically afforded by individual research projects. Strategies to promote such systems require a sufficiently long-term perspective that takes into account the generally slow diffusion of ideas and new scientific information in practice (Cash *et al.*, 2003; Van Kerkhoff and Lebel, 2006).

One way to build, maintain and strengthen synergy between research teams is to have a clear, over-arching funding system that co-ordinates research efforts and addresses clear national priorities. The current approach to research funding tends to focus on single projects or small groups of projects, and only provides a partial solution to the problem. The approach used so successfully by the Co-operative Scientific Programmes (CSP) to fund and guide research programmes during the 1980s could serve as a useful starting point for re-evaluating funding systems.

8 REFERENCES

ADAMS, J.B., BATE, G.C., HARRISON, T.D., HUIZINGA, P., TALJAARD, S., VAN NIEKERK, L., PLUMSTEAD, E., WHITFIELD, A.K. and WOOLDRIDGE, T.H. (2002). A method to assess the freshwater inflow requirements of estuaries and application to the Mtata Estuary, South Africa. *Estuaries*, **25**(6B): 1382-1393.

ALBUQUERQUE, E. (2003). Immature systems of innovation: introductory notes about a comparison between South Africa, India, Mexico and Brazil based on science and technology statistics. Discussion paper No 221. CEDEPLAR/FACE/IFMG, Belo Horizonte, Brazil.

ALEXANDER, W.J.A. (1982). *Water Requirements of the Pongola Floodplain System and Recommended Operating Rules for the Pongolapoort Dam*. Department of Water Affairs and Forestry, Pretoria, South Africa.

ALLANSON, B.R. (Ed). (1979). *Lake Sibaya*. Monographs in Biology, **36**. Dr W. Junk Publishers, The Hague, The Netherlands. 364 pages.

ALLANSON, B.R. (2003). Beacons in the limnological landscape. *African Journal of Aquatic Science*, **28**(2): 89-101.

ALLANSON, B.R. (2004). Limnology in South Africa: Past and present status and future needs. In: B. Gopal and R.W. Wetzel (eds), *Limnology in Developing Countries*, **4**: 1-116.

ALLANSON, B.R. and HART, R.C. (1975). The primary production of Lake Sibaya, KwaZulu, South Africa. *Verhandlungen internationale Vereinigung für theoretische und angewandte Limnologie,* **19**: 1426-1433.

ALLANSON, B.R., HART, R.C., O'KEEFFE, J.H., and ROBARTS, R.D. (1990). *Inland Waters of Southern Africa: An ecological perspective*. Monographiae Biologicae 64, Kluwer Academic Publishers, Dordrecht, The Netherlands. xiiii + 458 pages.

ALLANSON, B.R., HILL, B.J., BOLTT, R.E. and SCHULTZ, V. (1966). An estuarine fauna (fish, invertebrates) in a freshwater lake in South Africa. *Nature (London)*, **209**: 532-533.

ASHTON, P.J. (1977). Factors affecting the growth and development of *Azolla filiculoides* Lam. In: D.P. ANNECKE (Ed.), *Proceedings of the Second National Weeds Conference of South Africa*, pages 249-268. A.A. Balkema, Cape Town, South Africa.

ASHTON, P.J. (1979). Nitrogen fixation in a nitrogen-limited impoundment. *Journal of the Water Pollution Control Federation*, **51**(3): 570-579.

ASHTON, P.J. (1981). Nitrogen fixation and the nitrogen budget of a eutrophic impoundment. *Water Research*, **15**(7): 823-833.

ASHTON, P.J. (1982). *The Autecology of Azolla filiculoides Lamarck with Special Reference to its Occurrence in the Hendrik Verwoerd Dam Catchment Area*. Unpublished PhD Thesis, Rhodes University, Grahamstown, South Africa.

ASHTON, P.J. (2000). Potential environmental impacts associated with the proposed abstraction of water from the Okavango River in Namibia. *African Journal of Aquatic Science*, **25**:175-182.

ASHTON, P.J. (2002). Avoiding conflicts over Africa's water resources. *Ambio,* **31**(3): 236-242.

ASHTON, P.J. (2003). The search for an equitable basis for water sharing in the Okavango River basin. In: M. NAKAMURA (Ed.), *International Waters in Southern Africa*. United Nations University Press, Tokyo. Pages 164-188.

ASHTON, P.J. (2010). The demise of the Nile crocodile (*Crocodylus niloticus*) as a keystone species for aquatic ecosystem conservation in South Africa: The case of the Olifants River. *Aquatic Conservation: Marine and Freshwater Ecosystems*, **20**(5): 489-493.

ASHTON, P.J., EARLE, A., MALZBENDER, D., MOLOI, M.B.H., PATRICK, M.J. and TURTON, A.R. (2006). *A Compilation of All the International Freshwater Agreements Entered into by South Africa With Other States*. WRC Report No. 1515/1/06. Water Research Commission, Pretoria, South Africa.

ASHTON, P.J., HARDWICK, D. and BREEN, C.M. (2008). Changes in water availability and demand within South Africa's shared river basins as determinants of regional social-ecological resilience. In: M.J. BURNS and A.v.B. WEAVER (eds), *Exploring Sustainability Science: A Southern African Perspective*. Stellenbosch University Press, Stellenbosch, South Africa. Pages 279-310.

ASHTON, P.J. and MANLEY, R.E. (1999). Potential hydrological implications of water abstraction from the Okavango River in Namibia. In: *Proceedings of the Ninth South African Hydrological Symposium*, held at the University of Stellenbosch, from 29-30 November 1999. 11 pages.

ASHTON, P.J. and MITCHELL, D.S. (1989). Aquatic plants: patterns and modes of invasion, attributes of invading species and assessment of control programmes. Chapter 6, In: J.A. DRAKE, H.A. MOONEY, F. DI CASTRI, R.H. GROVES, F.J. KRUGER, M. REJMÁNEK and M. WILLIAMSON (eds), *SCOPE 37, Biological Invasions – A Global Perspective*. John Wiley & Sons, New York. Pages 111-154.

ASHTON, P.J., SCOTT, W.E., STEYN, D.J. and WELLS, R.D. (1979). The chemical control programme against the water hyacinth *Eichhornia crassipes* (Mart.) Solms on Hartbeespoort Dam: Historical and practical aspects. *South African Journal of Science*, **75**: 303-306.

ASHTON, P.J. and WALMSLEY, R.D. (1976). The aquatic fern *Azolla* and its *Anabaena* symbiont. *Endeavour*, **35**: 39-43.

ASHTON, P.J. and WALMSLEY, R.D. (1984). The taxonomy and distribution of *Azolla* species in southern Africa. *Botanical Journal of the Linnaean Society*, **89**: 239-247.

BALARIN, M.G., BRINK, E. and GLEN, H.P. (1999). Itinerary and specimen list of M.A. Pocock's botanical collecting expedition in Zambia and Angola in 1925. *Bothalia*, **29**(1): 159-201.

BARBOUR, M.T., GERRITSEN, J., SNYDER, B.D. and STRIBLING, J.B. (1999). *Rapid Bioassessment Protocols for Use in Streams and Wadeable Rivers: Periphyton, Benthic Macroinvertebrates and Fish*, Second Edition. EPA Report No. 841-B-99-002. U.S. Environmental Protection Agency, Office of Water, Washington, D.C.

BARNARD, K.H. (1947). *A Pictorial Guide to South African Fishes: Marine and Freshwater*. Maskew Miller, London.

BASSON, M.S., VAN NIEKERK, P.H. and VAN ROOYEN, J.N. (1997). *Overview of Water Resources Availability and Utilization in South Africa.* Report No. P RSA/00/0197. Department of Water Affairs and Forestry and BKS (Pty) Ltd., Pretoria, South Africa.

BEGG, G.W. (1978). *The Estuaries of Natal*. Natal Town and Regional Planning Report 41: 657 pages.

BEGG, G.W. (1984). *The Estuaries of Natal. Part 2.* Natal Town and Regional Planning Report 55: 631 pages.

BEGG, G.W. (1986). *The Wetlands of Natal (Part 1)*. Natal Town and Regional Planning Report, 68.

BEGG, G.W. (1988). The distribution, extent and status of wetlands in the Mfolozi catchment. *The Wetlands of Natal (Part 2)*. Natal Town and Regional Planning Report, 71.

BEINART, W. (2004). *The Rise of Conservation in South Africa: Settlers, Livestock, and the Environment 1770-1950*. Oxford University Press, Boston.

BELLERBY, C.W. (1934). A rapid test for the diagnosis of pregnancy. *Nature*, **133**:494-495.

BIGGS, H.C., BREEN, C.M., PALMER, C.G. (2008). Engaging a window of opportunity: synchronicity between a regional river conservation initiative and broader water law reform in South Africa. *International Journal of Water Resources Development*, **24**: 329-343.

BIGGS, R., WESTLEY, F.R. and CARPENTER, S.R. (2010). Navigating the back loop: fostering social innovation and transformation in ecosystem management. *Ecology and Society*, **15**(2): 9. [online] URL:http://www.ecologyandsociety.org/vol15/iss2/art9/

BIRD, M. and MALAN, H. (2010). *Aquatic Invertebrates as Indicators of Human Impacts in South African Wetlands*. WRC Report No. TT 435/09, Water Research Commission, Pretoria, South Africa.

BLABER, S.J.M. (1973). Temperature and salinity tolerance of juvenile *Rhabdosargus holubi* (Steindachner) (Teleostei: Sparidae). *Journal of Fish Biology,* **5**: 593-598.

BLABER, S.J.M. (1974). Field studies of the diet of *Rhabdosargus holubi* (Pisces: Teleostei: Sparidae). *Journal of Zoology, London,* **173**: 407-417.

BOND, G.W. (1946). *A Geochemical Survey of the Underground Water Supplies of the Union of South Africa with Particular Reference to their Utilisation in Power Production and Industry*. Department of Mines, Geological Survey Memoir No. 41. Government Printer, Pretoria, South Africa. 216 pages.

BOTES, D.P., TUINMAN, A.A., WESSELS, P.L., VILJOEN, C.C., KRUGER, H., WILLIAMS, D.H., SANTIKARN, S., SMITH, R.J. and HAMMOND, S.J. (1984). The structure of cyanoginosin-LA, a cyclic heptapeptide toxin from the cyanobacterium *Microcystis aeruginosa*. *Journal of the Chemistry Society, Perkin Translation, **1**:* 2311-2318.

BOZZOLI, G.R. (1997). *Forging Ahead: South Africa's Pioneering Engineers*. Witwatersrand University Press, Johannesburg, South Africa.

BREEN, C.M., DENT M., JAGANYI, J. MADIKIZELA, B., MGANABEHARIE, J., NDLOVU, A., O'KEEFFE, J. ROGERS, K.H. UYS, M and VENTER, F. (2000). *The Kruger National Park Rivers Research Programme*. WRC Report No. TT 130/00, Water Research Commission, Pretoria, South Africa.

BREEN, C.M. AND ASSOCIATES (2011). *The Review, Re-conceptualization, and Redesign of the Shared Rivers initiative: A structured and well-defined/described multi-disciplinary, long-term, shared rivers initiative/programme description with clear roles/responsibilities to ensure strategic policy support*. Consultancy Report KSA2: 8/964. Water Research Commission, Pretoria, South Africa.

BROWN, C.A., EEKHOUT, S. and KING, J.M. (1996). *National Biomonitoring Programme for Riverine Ecosystems: Proceedings of spatial framework workshop*. NBP Report Series No. 2. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

BROWN C.A. and JOUBERT, A. (2003). Using multi-criteria analysis to develop environmental flow scenarios for rivers targeted for water resource development. *Water SA*, **29**(4): 365-374.

BROWN, C.A., PEMBERTON, C., GREYLING, A. and KING, J.M. (2005). DRIFT user manual volume 1: Biophysical Module for predicting overall river condition in small to medium sized rivers with predictable flow regimes. WRC Report, Water Research Commission, Pretoria, South Africa.

BRUTON, M.N. (1979). The breeding biology and early development of *Clarias gariepinus* (Pisces: Clariidae) in Lake Sibaya, South Africa, with a review of breeding in species of the subgenus *Clarias* (*Clarias*). *Transactions of the Zoological Society of London,* **35**: 1-45.

BRUTON, M.N. and COOPER, K.H. (eds) (1980). *Studies on the Ecology of Maputaland*. Rhodes University, Grahamstown, and the Natal Branch of the Wildlife Society of South Africa, Durban, South Africa. 560 pages.

BRUWER, C., POULTNEY, C. and NYATHI, Z. (1996). Community-based hydrological management of the Phongolo floodplain. In: M.C. ACREMAN and G.E. HOLLIS (eds), *Water Management and Wetlands in Sub-Sahara Africa*. IUCN, Gland, Switzerland.

BUSH, V. (1945). *Science the Endless Frontier*. Report to President Roosevelt, United States Government Printing Office, Washington DC. Available (online) from: http://www.nsf.gov/about/history/vbush1945.htm (accessed 2 August 2011).

BUTTY, M. and WALMSLEY, R.D. (eds). (1979). *The Limnological Characteristics of 21 South African Impoundments*. Technical Report No. W 5/100/4/1/1, National Institute for Water Research, Council for Scientific and Industrial Research, Pretoria, South Africa; Part V of Document 6 – contract report to Water Research Commission, Pretoria.

CAMBRAY, J.A. (2003). The need of research and monitoring on the impacts of translocated sharptooth catfish, *Clarias gariepinus*, in South Africa. *African Journal of Aquatic Sciences*, **28(**2): 191-195.

CAMBRAY, J.A., KING, J.M. and BRUWER, C. (1997). Spawning behaviour and early development of the Clanwilliam yellowfish *(Barbus capensis*) linked to experimental dam releases in the Olifants River, South Africa. *Regulated Rivers: Research and Management,* **13**: 579-602.

CARRUTHERS, J. (2011). G. Evelyn Hutchinson in South Africa, 1926 to 1928: 'An immense part in my intellectual development'. *Transactions of the Royal Society of South Africa*, **66**(2): 87-104.

CARSON, R. (1962). *Silent Spring*. Houghton Mifflin Co., New York.

CASH, D.W., CLARK, W.C., ALCOCK, F., DICKSON, N.M., ECKLEY, N., GUSTON, D.H., JÄGER, J. and MITCHELL, R.B. (2003). Knowledge systems for sustainable development. *Proceedings of the National Academy of Science*, **100**: 8086-8091.

CEWM (COMMISSION OF ENQUIRY INTO WATER MATTERS) (1970). *Report of the Commission of Enquiry into Water Matters in South Africa*. Report RP 34/1970. Government Printer, Pretoria, South Africa.

CHERRY, M. (2010). South African science: black, white and grey. *Nature*, **463**: 726-728.

CHUTTER, F.M. (1972). An empirical biotic index of the quality of water in South African streams and rivers. *Water Research,* **6**: 19-30.

CHUTTER, F.M. (1994). The rapid biological assessment of streams and river water quality by means of macroinvertebrate communities in South Africa. In: M.C. UYS (Ed.), *Classification of Rivers and Environmental Health Indicators*. WRC Report No. TT 63/94. Water Research Commission, Pretoria, South Africa. Pages 217-234.

CHUTTER, F.M. (1998). *Research on the Rapid Biological Assessment of Water Quality Impacts in Streams and Rivers*. WRC Report No. 422/1/98. Water Research Commission, Pretoria, South Africa.

CILLIERS, C.J. (1991a). Biological control of water fern, *Salvinia molesta* (Salviniaceae), in South Africa. *Agriculture, Ecosystems and Environment*, **37**: 219-224.

CILLIERS, C.J. (1991b). Biological control of water lettuce, *Pistia stratiotes* (Araceae), in South Africa. *Agriculture, Ecosystems and Environment*, **37**: 225-230.

CILLIERS, C.J. (1999). Biological control of parrot's feather, *Myriophyllum aquaticum* (Vell) Verdc. (Haloragaceae), in South Africa. In: T. OLCKERS and M.P. HILL (eds), Biological Control of Weeds in South Africa (1990-1998). *African Entomology Memoir*, **1**: 113-118.

CILLIERS, C.J. and NESER, S. (1991). Biological control of water hyacinth, *Eichhornia crassipes* (Pontederiaceae), in South Africa. *Agriculture, Ecosystems and Environment*, **37**: 207-218.

CLARK, K., JARVIS, A.C., ASHTON, P.J. and ZOHARY, T. (1987). The use of TROPHIC as an aid for the management of eutrophic lakes. *Journal of the Limnological Society of Southern Africa*, **13**(2): 106-110.

CLARKE, D.J., HUGHES, D.A., MEIER, K.B. and SMITHERS, J.C. (2009). Development of a Hydrological Decision Support Framework. Paper presented at the 14th SANCIAHS Symposium, Pietermaritzburg, KwaZulu-Natal, South Africa, September 2009.

COCHRANE, K.L., ASHTON, P.J., JARVIS, A.C., TWINCH, A.J. and ZOHARY, T. (1987). A stratified ecosystem model of a warm, hypertrophic impoundment (Hartbeespoort Dam, South Africa). *Ecological Modelling*, **37**: 207-233.

COETZEE, J.A. (2001). Professor E.M. van Zinderen Bakker FRSSAf*. Transactions of the Royal Society of South Africa*, **56**(1): 52.

COOK, C.D.K. (2004). *Aquatic and Wetland Plants of Southern Africa*. Backhuys Publishers, Leiden, The Netherlands. 281 pages.

COWAN, G.I. (1995). Wetland Regions of South Africa. In G.I. COWAN (Ed.), *Wetlands of South Africa*. Department of Environmental Affairs and Tourism, Pretoria, South Africa.

COWAN, G.I. (Ed.) (1999). *Biota of Southern African Wetlands in Relation to the Ramsar Convention*. Department of Environmental Affairs and Tourism, Pretoria, South Africa.

COWAN, G.I. and VAN RIET, W. (1998). *A Directory of South African Wetlands.* Department of Environmental Affairs and Tourism, Pretoria, South Africa. 50 pages.

COWARDIN, L.M., CARTER, V., GOLET, F.C. and LA ROE, E.T. (1979). *Classification of Wetlands and Deepwater Habitats of the United States*. U.S. Department of the Interior, Fish and Wildlife Service, Washington DC.

CRASS, R.S. (1947). The mayflies (Ephemeroptera) of Natal and the Eastern Cape. *Annals of the Natal Museum*, **XI**(1): 37-110.

CRASS, R.S. (1964). *Freshwater Fishes of Natal*. Shuter and Shooter, Pietermaritzburg, South Africa.

CRASS, R.S. (1971). *Trout Fishing in Natal*. The Daily News, Durban, South Africa.

DADA, R., KOTZE, D., ELLERY, W. and UYS, M. (2007). *WET-Roadmap*. WRC Report No. TT 321/07, Water Research Commission, Pretoria, South Africa.

DALLAS, H. (1997). A preliminary evaluation of aspects of SASS (South African Scoring System) for the rapid bioassessment of water quality in rivers, with particular reference to the incorporation of SASS in a national biomonitoring programme. *Southern African Journal of Aquatic Sciences,* **23**(1): 79-94.

DALLAS, H.F. and DAY, J.A. (2007). Natural variation in macroinvertebrate assemblages and the development of a biological banding system for interpreting bioassessment data – a preliminary evaluation using data from upland sites in the south-western Cape, South Africa. *Hydrobiologia,* **575**(1): 231-244.

DALLAS, H.F., SEYMOUR, C., SNADDON, K. and EWART-SMITH, J. (2006). *Identification and Collation of Existing Information on the Wetlands of the Western Cape*. Report prepared for the Table Mountain Fund, WWF South Africa, Stellenbosch, South Africa. 112 pages.

DAVIES, B.R. and DAY, J.A. (1998). *Vanishing Waters*, second edition. University of Cape Town Press, Cape Town, South Africa.

DAVIES, B.R. and WALKER, K.F. (1986). *The Ecology of River Systems*. Springer Verlag, Berlin, Germany. 793pp.

DAVIES, B.R. and WALMSLEY, R.D. (eds) (1985). *Perspectives in Southern Hemisphere Limnology*. Proceedings of a Symposium held in Wilderness, South Africa, July 3-13, 1984. *Developments in Hydrobiology*, **28**. Dr W Junk Publishers, Dordrecht, The Netherlands.

DAY, E. and MALAN, H. (2009). *Tools and Metrics for Assessment of Wetland Environmental Condition and Socio-economic Importance: Handbook to the WHI Research Programme*. WRC Report No. TT 433/09, Water Research Commission, Pretoria, South Africa.

DAY, J.A., DAY, E., KETLEY, A., MALAN, H. and ROSS-GILLESPIE, V. (2010). *The Assessment of Temporary Wetlands During Dry Conditions*. WRC Report No. TT 434/09, Water Research Commission, Pretoria, South Africa.

DAY, J.H.O. (1981). *Estuarine Ecology with Special Reference to South Africa*. A.A. Balkema, Cape Town, South Africa.

DEAT (DEPARTMENT OF ENVIRONMENT AFFAIRS AND TOURISM) (2005). *South Africa's National Biodiversity Strategy and Action Plan.* Department of Environmental Affairs and Tourism, Pretoria, Pretoria.

DE KOK, K.N. (1973). *Die bevolkingsdinamika van vyf medies and veeartsnykundig belangrike varswaterslakspesies onder toestande van beheerde temperatuur*. Unpublished DSc thesis, Potchefstroom University, Potchefstroom, South Africa.

DE MEILLON, B., FRANK, G.H. and ALLANSON, B.R. (1958). Some aspects of snail ecology in South Africa: a preliminary report. *Bulletin of the World Health Organization*, **18**: 771-783.

DE MOOR, F.C. (l982). A community of *Simulium* species in the Vaal River near Warrenton. Ph.D. Thesis. 2 Volumes. University of the Witwatersrand, Johannesburg, South Africa. 3l7 pages.

DE MOOR, F.C. (1992a). Factors influencing the establishment of aquatic insect invaders. *Transactions of the Royal Society of South Africa,* **48**(1): 141-158.

DE MOOR, F.C. (1992b). Parasites, generalist and specialist predators and their role in limiting the population size of blackflies and in particular *Simulium chutteri* Lewis (Diptera: Simuliidae) in the Vaal River, South Africa. *Annals of the Cape Provincial Museum (Natural History),* **18**(13): 271-291.

DE MOOR, F.C. (1999). The use of Trichoptera to assess biodiversity and conservation status of South African river systems. pp 237-244. *In:* H. MALICKY (Ed.). *Proceedings of the 9th International Symposium on Trichoptera.* Chiang Mai, Peoples Republic of China.

DE MOOR, F.C. and CHUTTER, F.M. (1979). *Simulium chutteri*: A man-made problem species in South Africa. Abstract No.20, *Societas Internationale Limnologiae*. United Nations Environment Programme Workshop in African Limnology, Nairobi, Kenya. (Abstracts of poster papers).

DICKENS, C.W.S. and GRAHAM, P.M. (1998). Biomonitoring for effective management of wastewater discharges and the health of the river environment. *Aquatic Ecosystem Health and Management,* **1**: 199–217.

DICKENS, C.W.S. and GRAHAM, P.M. (2002). The South African Scoring System (SASS), version 5 rapid bioassessment method for rivers. *African Journal of Aquatic Science,* **27**(1): 1–10.

DOLD, A. (2001). Mary Agard Pocock: Botanical artist and intrepid explorer. *Veld and Flora*, **87**(4): 174-177.

DRIVER, A., MAZE, K., ROUGET, M., LOMBARD, A.T., NEL, J.L., TURPIE, J.K., COWLING, R.M., DESMET, P., GOODMAN, P., HARRIS, J., JONAS, Z., REYERS, B., SINK, K., STRAUSS, T. (2005). National spatial biodiversity assessment 2004: Priorities for biodiversity conservation in South Africa. *Strelitzia*, **17**: 1-45.

DU PREEZ, L. and CARRUTHERS, V. (2009). *A Complete Guide to the Frogs of Southern Africa.* Struik Nature, Cape Town, South Africa.

DU PREEZ, M., CONROY, R.M., LIGONDO, S., HENNESSY, J., ELMORE-MEEGAN, M. SOITA, A. and McGUIGAN, K.G. (2011). Randomized intervention study of solar disinfection of drinking water in the prevention of dysentery in Kenyan children aged under 5 years. *Environmental Science and Technology*, **45**: 9315-9323.

DWA (Department of Water Affairs) (1986). *Management of the Water Resources of the Republic of South Africa*. Department of Water Affairs, Pretoria, South Africa. 386 pages.

DWA (Department of Water Affairs) (1989). *Water Quality Management Policies and Strategies in the RSA*. Department of Water Affairs, Pretoria, South Africa. 38 pages.

DWAF (Department of Water Affairs and Forestry) (1996a). *National Biomonitoring Programme for Riverine Ecosystems: Proceedings of a consultation planning meeting.* NBP Report Series No. 5. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry) (1996b). *South African Water Quality Guidelines: Volume 7 – Aquatic Ecosystems*. Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry) (1999). *Resource Directed Measures for Protection of Water Resources. Volume 4: Wetland Ecosystems Version 1.0*. Department of Water Affairs and Forestry, Pretoria, South Africa.

DWAF (Department of Water Affairs and Forestry) (2004). *National Water Resource Strategy* (1st edition). Department of Water Affairs and Forestry, Pretoria, South Africa. Available (online) from: http://www. dwaf.gov.za/Documents/Policies/NWRS/Default.htm.

DWAF (Department of Water Affairs and Forestry) (2007). *Manual for the Assessment of a Wetland Index of Habitat Integrity for South African Floodplain and Channelled Valley Bottom Wetland Types*. Report No. N/000/00/WEI/0407. Resource Quality Services, Department of Water Affairs and Forestry, Pretoria.

EDMONDSON, Y.H. (1991). In memoriam: G. Evelyn Hutchinson (1903-1991). *Limnology and Oceanography*, **36**: 618.

EEKHOUT, S., BROWN, C.A. and KING, J.M. (1996). *National Biomonitoring Programme for Riverine Ecosystems: Technical considerations and protocols for the selection of reference and monitoring sites.* NBP Report Series No. 3. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

ELLERY, K. and ELLERY, W.N. (1997). *Plants of the Okavango Delta – a field guide*. Tsaro Publishers, Durban, South Africa. 225 pages.

ELLERY, W.N., GRENFELL, M., KOTZE, D.C., McCARTHY, T.S., TOOTH, S., GRUNDLING, P.-L., BECKEDAHL, H., LE MAITRE, D.C. and RAMSAY, L. (2008). *WET-Origins: Controls on the Distribution and Dynamics of Wetlands in South Africa*. WRC Report No. TT 334/08. Water Research Commission, Pretoria, South Africa.

ELLERY, W.N. and McCARTHY, T.S. (1994). Principles for the sustainable utilization of the Okavango Delta ecosystem, Botswana. *Biological Conservation*, **70**: 159-168.

EVERSON, C.S., DYE, P.J., GUSH, M.B. and EVERSON, T.M. (2011). Water use of grasslands, agroforestry systems and indigenous forests. *Water SA*, **37**: 781-788.

EWART-SMITH, J.L., OLLIS, D.J., DAY, J.A. and MALAN, H.L. (2006). *National Wetland Inventory: Development of a wetland classification system for South Africa*. WRC Report No. KV 174/06, Water Research Commission, Pretoria, South Africa.

FERRAR, A.A. (Ed.) (1989). *Ecological Flow Requirements of South African Rivers*. South African National Scientific Programmes Report No. 162. Foundation for Research Development, CSIR, Pretoria, South Africa.

FORBES, A.T. (1973). An unusual abbreviated larval life in the estuarine burrowing prawn *Callianassa kraussi* (Crustacea: Decapoda: Thalassinidea). *Marine Biology*, **22**: 361-365.

FREITAG, S**.**, BIGGS, H. and BREEN, C.M., (in review), Fifteen years of the spread and maturation of adaptive management in South African National Parks: organisational learning in systems perspective. In: W. FREIMUND, S. McCOOL AND C.M. BREEN (eds), *Engaging Complexity in Protected Area Management: Challenging Occam's Razor,* University of KwaZulu-Natal Press, Pietermaritzburg, South Africa.

FUNKE, N. and JACOBS, I. (2011). Integration challenges of water and land reform – A critical review of South Africa. In: U. UHLIG (Ed.), *Current Issues of Water Management*. InTech, Rijeka, Finland.

GAIGHER, C.M. (1973). Die status van inheemse vis in die Olifantsrivier. Cape Department of Nature and Environmental Conservation Internal Report, Stellenbosch, South Africa.

GAIGHER, I.G., HAMMAN, K.C.D. and THORNE, S.C. (1980). The distribution, conservation status and factors affecting the survival of indigenous freshwater fishes in the Cape Province. *Koedoe*, **23**: 57-88.

GEAR, J.H.S., PITCHFORD, R.J. and VAN EDEN, J.A. (1982). *Atlas of Bilharzia in South Africa*. Joint publication by South African Institute for Medical Research, South African Medical Research Council and Johannesburg Department of Health, Johannesburg, South Africa. 96 pages.

GERBER, A., CILLIERS, C.J., VAN GINKEL, C.E. and GLEN, R. (2004). *Easy Identification of Aquatic Plants: A guide for the identification of water plants in and around South African impoundments*. Department of Water Affairs and Forestry, Pretoria, South Africa.

GIBBONS, R.J. (1999). Informal authority in organizations. *Journal of Law, Economics and Organization*, **5**: 56-73.

GOUWS, A.C. and BOTHA, H.J. (2003). A walk through time of a surveying department. Department of Water Affairs, Pretoria, South Africa. Available (online) at:
http://www.dwa.gov.za/bi/Documents/Docs/A%2520WALK%2520THROUGH%2520TIME.pdf

GRENFELL, M.C., ELLERY, W.N. and GRENFELL, S.E. (2009). Valley morphology and sediment cascades within a wetland system in the KwaZulu-Natal Drakensberg Foothills, Eastern South Africa. *Catena*, **78**: 20-35.

GROBBELAAR, J.U. (1989). The contribution of phytoplankton productivity in turbid freshwater to their trophic status. *Hydrobiologia*, **173**: 127-133.

HARDING, W.R. (1996). *The Phytoplankton Ecology of a Hypertrophic Shallow Lake, with Particular Reference to Primary Production, Periodicity and Diversity*. Unpublished PhD Thesis, University of Cape Town, Cape Town, South Africa.

HARDING, W.R. (2008). *The Determination of Annual Phosphorus Loading Limits for South African Dams*. WRC Report No. 1687/1/08. Water Research Commission, Pretoria, South Africa.

HARDING, W.R., ARCHIBALD, C.G.M., TAYLOR, J.C. and MUNDREE, S. (2004). *The South African Diatom Collection: An appraisal and overview of needs and opportunities*. WRC Report No. TT 242/04. Water Research Commission, Pretoria, South Africa.

HARDING, W.R. and QUICK, A.J.R. (1992). Management options for shallow, hypertrophic lakes, with particular reference to Zeekoevlei, Cape Town. *South African Journal of Aquatic Science,* **18**(1/2): 3-19.

HARDING, W.R. and THORNTON, J.A. (1997). Eutrophication in African lakes, with particular reference to phosphorus loading. Fifth Session of the CIFA Working Party on Pollution and Fisheries, Ghana, 16-19 December 1998. FAO/FIR, Rome, Italy. 22 pp plus tables.

HARRISON, A.C. (1938). Fish of the Olifants River, Clanwilliam, south-western Cape Province. Freshwater Fisheries, Circular 31, Cape Piscatorial Society, Cape Town, 11pp.

HARRISON, A.C. (1952). The Cape witvis. *Piscator*, **21**: 25-26.

HARRISON, A.C. (1953). The acclimatization of smallmouth bass. *Piscator,* **27:** 89-96.

HARRISON, A.D. (1958a). Hydrobiological studies on the Great Berg River, Western Cape Province. Part 2. Quantitative studies on sandy bottoms, notes on tributaries and further information on the fauna, arranged systematically. *Transactions of the Royal Society of South Africa*, **35**: 227-276.

HARRISON, A.D. (1958b). Hydrobiological studies on the Great Berg River, Western Cape Province. Part 4. The effects of organic pollution on the fauna of parts of the Great Berg River System and the Krom Stream, Stellenbosch. *Transactions of the Royal Society of South Africa,* ***35****: 299-329.*

HARRISON, A.C. (1959). Orange River yellowfish introduced to the Gouritz River System. *Piscator*, **45**: 13-14.

HARRISON, A.D. (1962). Hydrobiological studies on alkaline and acid still waters in the Western Cape Province. *Transactions of the Royal Society of South Africa,* **36**: 213-243.

HARRISON, A.D. (1978). Freshwater invertebrates (except mollusks). Pages 1139-1152, In: M.J.A. WERGER and A.C. VAN BRUGGEN (eds), *Biogeography and Ecology of Southern Africa*. Monographiae Biologicae, 31. Dr W. Junk, The Hague, The Netherlands.

HARRISON, A.D. AND AGNEW, J.D. (1962). The distribution of invertebrates endemic to acid streams in the Western and Southern ape Province. *Annals of the Cape Provincial Museums,* **II**: 273-291.

HARRISON, A.D. and ELSWORTH, J.F. (1958). Hydrobiological studies on the Great Berg River, Western Cape Province. Part 1. General description, chemical studies and main features of the flora and fauna. *Transactions of the Royal Society of South Africa*, **35**: 125-226.

HART, R.C. (1977). Feeding rhythmicity in a migratory copepod (*Pseudodiaptomus hessei* (Mrázek)). *Freshwater Biology,* **7**: 1-8.

HART, R.C. (1978). Horizontal distribution of the copepod *Pseudodiaptomus hessei* in subtropical Lake Sibaya. *Freshwater Biology,* **8**: 415-421.

HART, R.C. (1980a). Oxygen consumption in *Caridina nilotica* (Decapoda: Atyidae) in relation to temperature and size. *Freshwater Biology,* **10**: 215-222.

HART, R.C. (1980b). Embryonic duration and post-embryonic growth rates of the tropical freshwater shrimp *Caridina nilotica* (Decapoda: Atyidae) under laboratory and experimental field conditions. *Freshwater Biology,* **10**: 297-315.

HART, R.C. (1981a). Population dynamics and production of the tropical freshwater shrimp *Caridina nilotica* (Decapoda: Atyidae) in the littoral of Lake Sibaya. *Freshwater Biology,* **11**: 531-547.

HART, R.C. (1983). Temperature tolerances and southern African distribution of a tropical freshwater shrimp *Caridina nilotica* (Decapoda: Atyidae). *South African Journal of Zoology,* **18**: 67-70.

HART, R.C. (1991). Food and suspended sediment influences on the naupliar and copepodid durations of freshwater copepods: comparative studies on *Tropodiaptomus* and *Metadiaptomus*. *Journal of Plankton Research,* **13**: 645-660.

HART, R.C. (1994b). Seasonal replacement in two calanoid copepods with equivalent adult dietary niches: the influence of temperature. *Verhandlungen internationale Vereinigung für theoretische und angewandte Limnologie,* **25**: 2439-2444.

HART, R.C. (1996). Comparative ecology of plankton in cascading warm-water reservoirs: aspects of relevance to tropical limnology. pp 113-130, In: F. SCHEIMER and K.T. BOLAND (eds). *Perspectives in Tropical Limnology*. SPB Academic Publishing bv, Amsterdam, The Netherlands.

HART, R.C. (1998). Copepod equiproportional development: experimental confirmation of its independence of food supply level, and a conceptual model accounting for apparent exceptions. *Hydrobiologia*, **380**: 77-85.

HART, R.C. (2001). Rapid estimation of *in situ* growth rates of *Caridina nilotica* (Crustacea: Decapoda) in Lake Victoria: Description and pilot application of a simple, field-compatible technique. *Limnology and Oceanography,* **46**: 692-698

HART, R.C. (2006a). Phytoplankton dynamics and periodicity in two cascading warm-water reservoirs from 1989 to 1997 – taxonomic and functional (C-S-R) patterns, and determining factors. *Water SA,* **32**: 81-92.

HART, R.C. (2006b). Food web (bio-)manipulation of South African reservoirs – viable eutrophication management prospect or illusory pipe dream? A reflective commentary and position paper. *Water SA,* **32**: 567-575.

HART, R.C. and ALLANSON, B.R. (1975). Preliminary estimates of production by a calanoid copepod in subtropical Lake Sibaya. *Verhandlungen internationale Vereinigung für theoretische und angewandte Limnologie,* **19**: 1434-1441.

HART, R.C. and ALLANSON, B.R. (1976). The distribution and diel vertical migration of *Pseudodiaptomus hessei* (Mrázek) (Calanoida: Copepoda) in a subtropical lake in southern Africa. *Freshwater Biology,* **6**: 183-198.

HART, R.C. and ALLANSON, B.R. (Eds) (1984). *Limnological Criteria for Management of Water Quality in the Southern Hemisphere*. South African National Scientific Programmes Report No. 93. Foundation for Research Development, Pretoria, South Africa. 181 pages.

HART, R.C., CAMPBELL, L.M. and HECKY, R.E. (2003). Stable isotope analyses and demographic responses counter prospects of planktivory by *Caridina* (Decapoda: Atyidae) in Lake Victoria. *Oecologia,* **136**: 270-278.

HART, R.C. and CHRISTMAS, G.L. (1984). A twin Gliwicz-Haney *in situ* zooplankton grazing chamber: design, operation and potential applications. *Journal of Plankton Research,* **6**: 715-719.

HART, R.C. and HART, R. (1977). The seasonal cycles of phytoplankton in subtropical Lake Sibaya: A preliminary investigation. *Archiv für Hydrobiologie,* **80**: 85-107.

HART, R.C. and JARVIS, A.C. (1993). *In situ* determinations of bacterial selectivity and filtration rates by five cladoceran zooplankters in a hypertrophic subtropical reservoir. *Journal of Plankton Research,* **15**: 295-315.

HEATH, R.G., ASHTON, P.J., CLAASSEN, M. and KING, N.D. (1995). *Crocodile River, Eastern Transvaal: Water Quality Situation Assessment – Final Report – 10 Volumes*. Department of Water Affairs and Forestry, Pretoria, South Africa. 1065 pages.

HEEG, J. and BREEN C.M. (1979). The Pongolo Floodplain: its functioning and role in the development of the Makatini Flats. An impact statement commissioned by the Secretary for Cooperation and Development, Government of the Republic of South Africa, Pretoria South Africa. 134 pages.

HEEG, J. and BREEN, C.M. (1982). *Man and the Pongolo Floodplain*. South African National Scientific Programmes Report No. 56. CSIR, Pretoria, South Africa. 117 pages.

HEY, D. (1939). A preliminary report concerning the low fertility of trout eggs at the Jonkershoek hatchery. *Annals of the University of Stellenbosch*, 17 Section A, No. 1.

HEY, D. (1949). The culture of the South Africa clawed frog *Xenopus laevis* (Daudin) at the Jonkershoek Inland Fish Hatchery. *Transactions of the Royal Society of South Africa*, **32**(1): 45-54.

HEY, D. (1952). *Fish Keeping in Ponds and Aquaria*. Department of Nature Conservation, Cape Province, South Africa.

HEY, D. (1971). *Practical Freshwater Fish Culture*. Department of Nature Conservation, Cape Province, South Africa.

HEY, D. (1995). *A Nature Conservationist Looks Back*. Cape Nature Conservation. 280 pages.

HEY, S.A. (1924). *Guide to Trout Fishing in South Africa*. South African Railways, Cape Town, South Africa.

HEY, S.A. (1926). Preliminary report on the Inland Waters of South Africa with regard to the suitability for the introduction of edible fish. Report to the Department of Mines and Industries, Cape Town, South Africa.

HILL, B.J. (1975). Abundance, breeding and growth of the crab *Scylla serrata* in two South African estuaries. *Marine Biology,* **32**: 119-126.

HILL, B.J. (1977). The effect of heated effluent on egg production in the estuarine prawn *Upogebia africana* (Ortmann). *Journal of Experimental Marine Biology and Ecology,* **29**: 291-302.

HILL, B.J. and ALLANSON, B.R. (1971). Temperature tolerance of the estuarine prawn *Upogebia africana* (Anomura, Crustacea). *Marine Biology,* **11**: 337-343.

HILL, M.P. (2003). The impact and control of alien aquatic vegetation in South African aquatic ecosystems. *African Journal of Aquatic Science*, **28**(1): 19-24.

HILL, M.P. and COETZEE, J.A. (2008). Integrated control of water hyacinth in Africa. *EPPO Bulletin*, **38**: 452-457.

HILL, M.P., McCONNACHIE, A.J. and BYRNE, M.J. (2007). *Azolla filiculoides* Lamarck (Pteridophyta: Azollaceae) control in South Africa: A 10-year review. *Proceedings of the XII International Symposium on Biological Control of Weeds*. Pages 566-568.

HODGSON, A.N. and CRAIG, A.J.F.K. (2005). A century of zoology and entomology at Rhodes University, 1905 to 2005. *Transactions of the Royal Society of South Africa,* **60**(1): 1-18.

HOHLS, D.R. (1996). *National Biomonitoring Programme for Riverine Ecosystems: Framework document for the programme.* NBP Report Series No. 1. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

HOWELL, C.J., BEGEMAN, G.J., MUIR, R.W. and LOUW, P. (1981). The control of Simulidae (Diptera, Nematocera) in South African rivers by modification of the water flow volume. *Onderstepoort Journal of Veterinary Research*, **48**: 47-49.

HUGHES, D.A. (Ed). (2004). *SPATSIM, An Integrating Framework for Ecological Reserve Determination and Implementation*. WRC Report No TT 245/04. Water Research Commission, Pretoria, South Africa

HUGHES, D.A. and HANNART, P. (2003). A desktop model used to provide an initial estimate of the ecological instream flow requirements of rivers in South Africa. *Journal of Hydrology*, **270**: 167-181.

HUGHES, D.A. and FORSYTH, D.A. (2006) A generic database and spatial interface for the application of hydrological and water resource models. *Computers and Geosciences*, **32**: 1389-1402.

HUGHES, D.A. and LOUW, D. (2010). Integrating hydrology, hydraulics and ecological response into a flexible approach to the determination of environmental water requirements for rivers. *Environmental Modeling and Software*, **25**(8): 910-918.

HUTCHINSON, G.E. (1929). A revision of the Notonectidae and Corixidae of South Africa. *Annals of the South African Museum,* **25**: 359-474

HUTCHINSON, G.E. (1957). *A Treatise on Limnology. Volume 1: Geography, Physics and Chemistry*. John Wiley & Sons, New York.

HUTCHINSON, G.E. (1967). *A Treatise on Limnology Volume 2: Introduction to Lake Biology and the Limnoplankton*. John Wiley & Sons, New York.

HUTCHINSON, G.E. (1975). *A Treatise on Limnology Volume 3: Limnological Botany*. John Wiley & Sons, New York.

HUTCHINSON, G.E. (1993). *A Treatise on Limnology Volume 4: The Zoobenthos*. John Wiley & Sons, New York.

HUTCHINSON, G.E., PICKFORD, G.E. and SCHUURMAN, A. (1932). A contribution to the hydrobiology of pans and other inland waters of South Africa. *Archiv für Hydrobiologie*, **24**: 1-154.

HYNES, H.B.N. (1970). *The Ecology of Running Waters*. University of Toronto Press, Toronto, Canada. 555 pages.

JARVIS, A.C. and HART, R.C. (1993). Determining *in situ* bacterial filtration rates by zooplankton: Improvements to the [methyl-^{3}H]-thymidine labelling technique. *Journal of Plankton Research,* **15**: 277-294.

JARVIS, A.C., HART, R.C. and COMBRINK, S. (1987). Zooplankton feeding on size fractionated *Microcystis* colonies and *Chlorella* in a hypertrophic lake (Hartbeespoort Dam, South Africa): implications to resource utilization and zooplankton succession. *Journal of Plankton Research,* **9**: 1231-1249.

JARVIS, A.C., HART, R.C. and COMBRINK, S. (1988). Cladoceran filtration rate-body length relations: model improvements developed for a *Microcystis* dominated hypertrophic reservoir. *Journal of Plankton Research,* **10**: 115-131.

JORDANOVA, A.A., JAMES, C.S. and BIRKHEAD, A.L. (2006). Practical resistance estimation for flow through emergent vegetation. *Journal of Water Management of ICE*, **159**: issue WM3, pp 173-181.

JOUBERT, S. (2007). *The Kruger National Park: A History*. Vols I-III. High Branching, Johannesburg, South Africa.

JUBB, R.A. (1967). *Freshwater Fishes of Southern Africa*. A.A. Balkema, Cape Town, South Africa. 257 pages.

KAHNMAN, D. (2011). *Thinking, Fast and Slow*. Farrar, Straus and Giroux, New York.

KALFF, J. (2002). *Limnology*. Prentice Hall Publishers, New Jersey.

KARR, J.R., FAUSCH, K.D., ANGERMEIER, P.L., YANT, P.R., and SCHLOSSER, I.J. (1986). *Assessing Biological Integrity in Running Waters – a method and its rationale.* Illinois Natural History Survey, Special Publication 5, Champaign, Illinois.

KENT, L.E. (1949). The thermal waters of the Union of South Africa and South West Africa. *Transactions of the Geological Society of South Africa*, **52**: 231-264.

KING, J.M., BROWN, C.A. and SABET, H. (2003). A scenario-based holistic approach to environmental flow assessments for rivers. *River Research Applications*, **19**(5-6): 619-639.

KING, J.M. and LOUW, D. (1998). Instream flow assessments for regulated rivers in South Africa using the Building Block Methodology. *Aquatic Ecosystems Health and Restoration*, **1**: 109-124.

KING, J.M. and PIENAAR, H.H. (eds) (2011). *Sustainable Use of South Africa's Inland Waters: A situation assessment of Resource Directed Measures 12 years after the 1998 National Water Act*. WRC Report No. TT 491/11. Water Research Commission, Pretoria, South Africa.

KING, J.M. and THARME, R.E. (1994). *Assessment of the Instream Flow Incremental Methodology and Initial Development of Alternative Instream Flow Methodologies for South Africa*. WRC Report No. 295/1/94. Water Research Commission, Pretoria, South Africa. 590 pages.

KING, J.M., THARME, R.E. and DE VILLIERS, M. (eds) (2000). *Environmental Flow Assessments for Rivers: Manual for the Building Block Methodology*. WRC Report TT 131/00. Water Research Commission, Pretoria, South Africa. 340 pages.

KINGSFORD, R.T., BIGGS, H.C, and POLLARD, S.R. (2011) Strategic Adaptive Management in freshwater protected areas and their rivers. *Biological Conservation*, **144**: 1194-1203.

KINGWILL, D.G. (1990). *The CSIR: The First 40 Years*. CSIR, Pretoria, South Africa.

KISTIN, E.J. and ASHTON, P.J. (2008). Adapting to change on transboundary rivers: An analysis of treaty flexibility on the Orange-Senqu River basin. *International Journal of Water Resources Development*, **24**(2): 385-400.

KISTIN, E.J., ASHTON, P.J., TURTON, A.R., PATRICK, M.J., EARLE, A. and MALZBENDER, D. (2009). An overview of the content and historical context of the international freshwater agreements that South Africa has entered into with neighbouring countries. *International Environmental Agreements: Politics, Law and Economics*, **9**(1): 1-21.

KLEYNHANS, C.J. (1996). A qualitative procedure for the assessment of the habitat integrity status of the Luvuvhu River (Limpopo system, South Africa). *Journal of Aquatic Ecosystem Health,* **5**: 41-54.

KLEYNHANS, C.J. (1999). The development of a fish index to assess the biological integrity of South African rivers. *Water SA,* **25**(3): 265-278.

KLEYNHANS, C.J. (2007). *Module D: Fish Response Assessment Index in River EcoClassification: Manual for EcoStatus Determination (Version 2)*. Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No. TT 330/08. Water Research Commission, Pretoria, South Africa.

KLEYNHANS, C.J. and LOUW, M.D. (2007). *Module A: EcoClassification and EcoStatus determination in River EcoClassification: Manual for EcoStatus Determination (version 2)*. Joint Water Research Commission and Department of Water Affairs and Forestry report. WRC Report No TT 330/08. Water Research Commission, Pretoria, South Africa.

KLEYNHANS, C.J., THIRION, C. and MOOLMAN, J. (2005). *A Level I River Ecoregion Classification System for South Africa, Lesotho and Swaziland.* Report No. N/0000/00/REQ0104. RQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

KLEYNHANS, C.J, THIRION, C. MOOLMAN, J. and GAULANA, L. (2007). *A Level II River Ecoregion Classification System for South Africa, Lesotho and Swaziland.* RQS Report No. N/0000/00/REQ. Resource Quality Services, Department of Water Affairs and Forestry, Pretoria, South Africa.

KOTZE, D.C. and O'CONNOR, T.G. (2000). Vegetation pattern within and among palustrine wetlands along an altitudinal gradient in KwaZulu-Natal, South Africa. *Plant Ecology*, **146**: 77-96.

KOTZE, D.C., KLUG, J.R., HUGHES, J.C. and BREEN, C.M. (1996). Improved criteria for classifying hydric soils in South Africa. *South African Journal of Plant and Soil*, **13**: 67-73.

KRUCHEM, T. (2012). *Orange-Senqu: Artery of Life. Water and Peace in Southern Africa*. Brandes & Apsel, Frankfurt am Main, Germany.

LANDON, D.B. (2005). Zooarchaeology and historical archaeology: Progress and prospects. *Journal of Archaeological Method and Theory*, **12**(1): 24.

LE MAITRE, D.C., GAERTNER, M., MARCHANTE, E., ENS, E.-J., HOLMES, P.M., PAUCHARD, A., O'FARRELL, P.J., ROGERS, A.M., BLANCHARD, R., BLIGNAUT, J. and RICHARDSON, D.M. (2011). Impacts of invasive Australian Acacias: implications for management and restoration. *Diversity and Distributions*, **17**: 1015-1029.

LEVITT, B. and MARCH, J.G. (1988). Organizational learning. *Annual Review of Sociology*, **14**: 319-340

LOWE, S.R., WOODFORD, D.J., IMPSON, D.N. and DAY, J.A. (2005). The impact of invasive fish and invasive riparian plants on the invertebrate fauna of the Rondegat River in the Cape Floristic region, South Africa. *African Journal of Aquatic Sciences,* **33**(1): 51-63.

LINDEMAN, R.L. (1942). The trophic-dynamic aspect of ecology. *Ecology*, **23**: 399-418.

LUBSCHENCO, J. (1998). Entering the century of the environment: a new social contract for science. *Science*, **279**: 491-497.

MADZIVIRE, G., GITARI, W.M., VADAPALI, V.R.K., OJUMU, T.V. and PETRIK, L.F. (2011). Fate of sulphate removed during the treatment of circum-neutral mine water and acid mine drainage with coal fly ash: modeling and experimental approach. *Minerals Engineering*, **24**: 1467-1477.

MALAN, H. and DAY, J.A. (2005). *Predicting Water Quality and Biotic Response in Ecological Reserve Determinations*. WRC Report No. TT 202/02. Water Research Commission, Pretoria, South Africa.

MALAN, H.L. and DAY, J.A. (2010). *Strategic Overview of the Research Needs for Wetland Health and Integrity*. WRC Report No. KV 171/05. Water Research Commission, Pretoria, South Africa.

McCARTHY, T.S., ARNOLD, V., VENTER, J. and ELLERY, W.N. (2007). The collapse of Johannesburg's Klip River Wetland. *South African Journal of Science*, **103**: September/October.

McCARTHY, T.S., BLOEM, A. and LARKIN, P.A. (1998). Observations on the hydrology and geohydrology of the Okavango Delta. *South African Journal of Geology*, **101**(1): 117.

McCARTHY, T.S., COOPER, G.R.J., TYSON, P.D. and ELLERY, W.N. (2000). Seasonal flooding in the Okavango Delta, Botswana – recent history and future prospects. *South African Journal of Science*, **96**(1): 25-33.

McCARTHY, T.S. and ELLERY, W.N. (1998). The Okavango Delta. *Transactions of the Royal Society of South Africa,* **53**(2):157-182.

McCARTHY, T.S., TOOTH, S., KOTZE, D.C., COLLINS, N.B., WANDRAG, G. and PIKE, T. (2010). The role of geomorphology in evaluating remediation options for floodplain wetlands: the case of Ramsar-listed Seekoevlei, eastern South Africa. *Wetlands Ecology and Management*, **18**: 119-134.

McCONNACHIE, A.J., DE WIT, M.P., HILL, M.P. and BYRNE, M.J. (2003). Economic evaluation of the successful biological control of *Azolla filiculoides* in South Africa. *Biological Control*, **28**: 25-32.

MIDGLEY, D.C., PITMAN W.V. and MIDDLETON, B.J. (1994). *Surface Water Resources of South Africa 1990*. WRC Report No 298/94. Water Research Commission, Pretoria, South Africa.

MIDDLETON, B.J. and BAILEY, A.K. (2009). *Water Resources of South Africa, 2005 Study (WR2005)*. WRC Report No. TT 380/08. Water Research Commission, Pretoria, South Africa.

MINTER, L.R., BURGER, M., HARRISON, J.A., BRAACK, H.H., BISHOP, P.J. and KLOEPFER, D. (eds). (2004). *Atlas and Red Data Book of the Frogs of South Africa, Swaziland and Lesotho.* SI/MAB Series #9. Smithsonian Institution, Washington D.C.

MITSCH, W.J. and GOSSELINK, J.G. (1986). *Wetlands*. Van Nostrand Reinhold, New York. 539 pages.

MOORE, C.A., VAN VEELEN, M., ASHTON, P.J. and WALMSLEY, R.D. (1991). *Preliminary Water Quality Guidelines for the Kruger Park Rivers*. Kruger National Park Rivers Research Programme Report No.1. Foundation for Research Development, Pretoria, South Africa. 91 pages.

MOSS, B. (1999). *Eutrophication and Eutrophication Research in South Africa – An Independent View*. Contract report to Lever Brothers (South Africa), Johannesburg, South Africa. 15 pages.

MUASYA, A.M. and SIMPSON, D. (2002). A monograph on the genus *Isolepis* R.Br. (Cyperaceae). *Kew Bulletin,* **57**: 257-362.

MURRAY, K. (1999). *National Biomonitoring Programme for Riverine Ecosystems: National Implementation Assessment.* NBP Report Series No. 8. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

MUSEE, N. (2011). Nanowastes and the environment: potential new waste management paradigm. *Environment International*, **37**: 112-128.

MUSEE, N., BRENT, A.C. and ASHTON, P.J. (2010). A South African research agenda to investigate the potential environmental, health and safety risks of nanotechnology. *South African Journal of Science*, **106**(3/4): 1-6.

NEL, J.L., ROUX, D.J., COWLING, R.M., ABELL, R., ASHTON, P.J., HIGGINS, J.A., THIEME, M., VIERS, J.C. (2009). Progress and challenges in freshwater conservation planning. *Aquatic Conservation: Marine and Freshwater ecosystems*, **19**: 474-485.

NEL, J.L., DRIVER, A., STRYDOM, W.F., MAHERRY, A., PETERSEN, C., HILL, L., ROUX, D.J., NIENABER, S., VAN DEVENTER, H., SWARTZ, E. and SMITH-ADAO, L.B. (2011a). *Atlas of Freshwater Ecosystem Priority Areas in South Africa*. WRC Report No. TT 500/11. Water Research Commission, Pretoria, South Africa.

NEL, J.L., REYERS, B., ROUX, D.J., IMPSON, N.D. and COWLING, R.M. (2011b). Designing a conservation area network that supports the representation and persistence of freshwater biodiversity. *Freshwater Biology*, **56**: 106-124.

NIWR (National Institute for Water Research) (1985). *The Limnology of Hartbeespoort Dam*. South African National Scientific Programmes Report No. 110. Foundation for Research Development, CSIR, Pretoria, South Africa. 269 pages.

NOBLE, R.G. (1974). An evaluation of the conservation status of aquatic biotopes. *Koedoe,* **17**: 71-83.

NOBLE, R.G. and HEMENS, J. (1978). *Water Ecosystems in South Africa – A review of research needs.* National Scientific Programmes Report **34**, CSIR, Pretoria, South Africa. 160 pages.

OBERHOLSTER, P.J., MYBURGH, J.G., ASHTON, P.J. and BOTHA, A.-M. (2010). Responses of phytoplankton upon exposure to a mixture of acid mine drainage and high levels of nutrient pollution in Lake Loskop, South Africa. *Ecotoxicology and Environmental Safety*, **73**(3): 326-335.

OCKERSE, T. (1946). *Endemic Fluorosis in South Africa*. University of the Witwatersrand, Johannesburg, South Africa. Available (online) from: http://www.worldcat.org/oclc/11898330.

ODUM, E.P. (1953). *Fundamentals of Ecology*. W.B. Saunders Co., Philadelphia and London. 384 pages.

O'FARRELL, P.J., De LANGE, W.J., LE MAITRE, D.C., REYERS, B., BLIGNAUT, J.N., MILTON, S.J., ATKINSON, D., EGOH, B., MAHERRY, A., COLVIN, C. and COWLING, R.M. (2011). The possibilities and pitfalls presented by a pragmatic approach to ecosystem service evaluation in an arid biodiversity hotspot. *Journal of Arid Environments*, **75**: 612-623.

O'KEEFFE, J.H. (Ed.) (1986). *The Conservation of South African Rivers*. South African National Scientific programmes Report No. 131. Foundation for Research Development, CSIR, Pretoria, South Africa.

O'KEEFFE, J.H. (1989). Conserving rivers in southern Africa. *Biological Conservation,* **49**: 255-274.

O'KEEFFE, J.H., DANILEWITZ, D.B. and BRADSHAW, J.A. (1987). An 'expert system' approach to the assessment of the conservation status of rivers. *Biological Conservation*, **40**: 69-84

O'KEEFFE, J.H., DAVIES, B.R., KING, J.M. and SKELTON, P.H. (1989). The conservation status of southern African rivers. In: B.J. BUNTLEY (Ed.), *Biotic Diversity in Southern Africa*. Oxford University Press, Cape Town, South Africa. Pages 276-299.

O'KEEFFE, J.H., HUGHES, D.H. and THARME, R.E. (2002). Linking ecological responses to altered flows, for use in environmental flow assessments: the Flow Stressor-Response method. *Verhandlunging der Internationale Vereinigung der Limnologie*, **28**: 84-92

O'KEEFFE, J.H. and ROGERS, K.H. (2003) Heterogeneity and the management of Lowveld rivers. P. 447-466. P. 370-388. In: R. DU TOIT, K.H. ROGERS and H.C. Biggs (eds), *The Kruger Park Experience – Ecology and Management of Savanna Heterogeneity*. Island Press, Washington DC.

PALLETT, J. (Ed.) (1997). *Sharing Water in Southern Africa.* Desert Research Foundation of Namibia, Windhoek, Namibia.

PALMER, C.G. (1999). The application of ecological research in the development of a new water law in South Africa. *Journal of the North American Benthological Society*, **18**: 132-142.

PALMER, C.G. (2010). *Concept Document: Akili Complexity and Integration Programme within Human and Social Dynamics in Development Grand Challenge*. National Research Foundation, Pretoria, South Africa.

PALMER, C.G., ROSSOUW, J.N., SCHERMAN, P.-A. and MULLER, W.J. (2005). The development of water quality methods within ecological Reserve assessments, and links to environmental flows. *Water SA*, **31**: 161-170.

PASSMORE, N.I. and CARRUTHERS, V.C. (1979). *South African Frogs.* Witwatersrand University Press, Johannesburg, South Africa. 279 pages.

PHILLIPS, H. (1990). *Black October – The Impact of the Spanish Influenza Epidemic of 1918 on South Africa*. Government Printer, Pretoria, South Africa.

PIENAAR, U. De V. (1968). *The Freshwater Fishes of the Kruger National Park*. National Parks Board, Pretoria, South Africa. 81 pages.

PIENAAR, U. De V. (1978). *The Freshwater Fishes of the Kruger National Park*. Second Edition. National Parks Board, Pretoria, South Africa. 91 pages.

PITCHFORD, R.J. and VISSER, P.S. (1975). The effect of large dams on river water temperature below the dams, with special reference to bilharzia and the Verwoerd Dam. *South African Journal of Science*, **71**(7): 212-213.

POLLARD, S. and DU TOIT. D. (2009). Drawing Environmental Water Allocations into the World of Realpolitik: Emerging Experiences on Achieving Compliance with Policy in the Lowveld Rivers, South Africa. Implementing Environmental Flow Allocations, Port Elizabeth, South Africa.

POTE, J. (1996). Historical highlights: The J.L.B. Smith Institute of Ichthyology and the Department of Ichthyology and Fisheries Science 1946-1996. *Transactions of the Royal Society of South Africa*, **51**: 5-31.

POYNTON, J.C. (1964). The Amphibia of southern Africa: a faunal study in 1964. *Annals of the Natal Museum,* **17:** 1-334.

QUICK, A.J.R. and HARDING, W.R. (1994). Management of a shallow estuarine lake for recreation and as a fish nursery: Zandvlei, Cape Town, South Africa. *Water SA,* **20**(4): 289-297.

RIBBINK, A.J. (1977). Cuckoo among Lake Malawi cichlid fish. *Nature,* **267**: 243-244.

RIBBINK A.J., MARSH, B.J., MARSH, A.C., RIBBINK, A.C. and SHARP, B.J. (1983). A preliminary survey of the cichlid fishes of the rocky habitats of Lake Malawi. *South African Journal of Zoology*, **18**: 149-310.

ROBERTS, C.P.R. (1981). *Environmental Considerations of Water Projects*. Technical Report 114, Department of Water Affairs, Pretoria, South Africa.

ROBERTS, C.P.R. (1983). Environmental constraints on water resource development. *Proceedings of the South African Institute of Civil Engineers Annual Conference*, **1**: 16-23.

ROGERS, K.H. (2006). The real river management challenge: Integrating Scientists, Stakeholders and Service Agencies. *River Research and Application*, **22**: 269-280.

ROGERS, K.H. (2008). Limnology and the post-normal imperative: an African perspective. *Verhandlungen des Internationale Vereinigung der Limnologie*, **30**(2): 171-185.

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, South Africa.

ROGERS, K.H. and BIGGS, H.C. (1999). Integrating indicators, endpoints and value systems in strategic management of the Kruger National Park. *Freshwater Biology*, **41**: 439-451.

ROGERS, K. and O'KEEFFE, J.H. (2003). River Heterogeneity: Ecosystem structure, function and management. In*:* R. DU TOIT, K.H. ROGERS and H.C. BIGGS (eds), *The Kruger Park Experience – Ecology and Management of Savanna Heterogeneity*. Island Press, Washington DC.

ROSE, W. (1962). *The Reptiles and Amphibians of Southern Africa.* Maskew Miller, Cape Town, South Africa.

ROSSOUW, J.N., HARDING, W.R., and FATOKI, O.S. (2008). *A Guide to Catchment-scale Eutrophication Assessments for Rivers, Reservoirs and Lacustrine Wetlands*. WRC Report No. 1643/1/08. Water Research Commission, Pretoria, South Africa.

ROUX, D.J. (1997). *National Biomonitoring Programme for Riverine Ecosystems: Overview of the design process and guidelines for implementation.* NBP Report Series No. 6. IWQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

ROUX, D.J., NEL, J.L., ASHTON, P.J., DEACON, A.R., DE MOOR, F.C., HARDWICK, D., HILL, L., KLEYNHANS, C.J., MAREE, G.A., MOOLMAN, J. and SCHOLES, R.J. (2008). Designing protected areas to conserve riverine biodiversity: Lessons from a hypothetical redesign of the Kruger National Park. *Biological Conservation,* **141**(1): 100-117.

ROUNTREE, M.W. and MALAN, H. (eds) (2010). *Rapid Ecological Reserve Determination Methods for Wetlands (Version 2.0).* Joint Department of Water Affairs and Water Research Commission Study. WRC Report. Water Research Commission, Pretoria, South Africa.

RSA (REPUBLIC OF SOUTH AFRICA) (1997). *The Water Services Act (Act No. 108 of 1997)*. Government of the Republic of South Africa, Pretoria, South Africa.

RSA (REPUBLIC OF SOUTH AFRICA) (1998). *The National Water Act (Act No. 36 of 1998)*. Government of the Republic of South Africa, Pretoria, South Africa.

SADC (SOUTHERN AFRICAN DEVELOPMENT COMMUNITY) (2001). *Revised Protocol on Shared Watercourse Systems in the Southern African Development Community (SADC) Region*. Southern African Development Community, Windhoek, Namibia.

SANBI (SOUTH AFRICAN NATIONAL BIODIVERSITY INSTITUTE) (2009). *Further Development of a Proposed National Wetland Classification System for South Africa. Primary Project Report*. Prepared by the Freshwater Consulting Group (FCG) for the South African National Biodiversity Institute, Pretoria, South Africa.

SCHELPE, E.A.C.L.E. and ANTHONY, N.C. (1986). Pteridophyta. *Flora of Southern Africa.* 292 pages.

SCHUURMAN, J.F.M. (1932). A seasonal study of the microflora and micro-fauna of Florida lake, Johannesburg, Transvaal. *Transactions of the Royal Society of South Africa,* **20**: 333-386.

SCOTT, K.M.F. (1958). Hydrobiological studies on the Great Berg River, Western Cape Province. Part 3. The Chironomidae. *Transactions of the Royal Society of South Africa,* **35**: 277-298.

SCOTT, W.E., ASHTON, P.J. and STEYN, D.J. (1979). *Chemical Control of the Water Hyacinth on Hartbeespoort Dam*. Water Research Commission, Pretoria, South Africa. 84 pages.

SCOTT, W.E., ASHTON, P.J., WALMSLEY, R.D. and SEAMAN, M.T. (1980). Hartbeespoort Dam: a case study of a hypertrophic, warm, monomictic impoundment. *Developments in Hydrobiology*, **2**, Special Issue: *Hypertrophic Ecosystems*, J. BARICA and L.R. MUR (eds): 317-322.

SCOTT, J.M., DAVIS, F., CSUIT, B., NOSS, R., BUTTERFIELD, B., GROVES, C., ANDERSON, H., CAICCO, S., D'ERCHIA, F., EDWARDS, T.C., ULLIMAN, J. and WRIGHT, R.G. (1993). Gap Analysis: A geographic approach to protection of biological diversity. *Wildlife Monographs,* **123:** 3-41.

SEAMAN, M.T., ASHTON, P.J. and WILLIAMS, W.D. (1991). Inland salt waters of southern Africa. *Hydrobiologia*, **210** (1-2): 75-91.

SEAMAN, M.T., AVENANT, M.F., WATSON, M., KING, J., ARMOUR, J., BARKER, C.H., DOLLAR, E., DU PREEZ, P.J., HUGHES, D.H., ROSSOUW, L., and VAN TONDER, G. (2010). *Developing a Method for Determining the Environmental Water Requirements for Non-perennial Systems*. WRC Report No. TT 459/10. Water Research Commission, Pretoria, South Africa.

SHAPIRO, H.A. and ZWARENSTEIN, H. (1934). A rapid test for pregnancy on *Xenopus laevis*. *Nature*, **133**: 762.

SIEBEN, E.J.J., MORRIS, C.D., KOTZE, D.C. and MUASYA, A.M. (2010). Changes in plant form and function across altitudinal and wetness gradients in the wetlands of the Maloti-Drakensberg, South Africa. *Plant Ecology*, **207**: 107-119.

SILBERBAUER, M.J. and KING, J.M. (1991a). The distribution of wetlands in the South-Western Cape Province, South Africa. *South African Journal of Aquatic Sciences* **17**(1/2): 65-81.

SILBERBAUER, M.J. and KING, J.M. (1991b). Geographical trends in the water chemistry of wetlands in the south-western Cape Province, South Africa. *South African Journal of Aquatic Sciences,* **17**(1/2): 82-88.

SKELTON, P.H. (1993). *Freshwater Fishes of Southern Africa*. Southern Book Publishers, Halfway House, South Africa.

SKELTON, P.H. (1997). A historical review of the taxonomy and biogeography of freshwater fishes in South Africa – the past 50 years. *Transactions of the Royal Society of South Africa*, **51**: 91-114.

SKELTON, P.H. (2001)**.** *A Complete Guide to the Freshwater Fishes of Southern Africa.* Struik, Cape Town. 395 pages.

SKELTON, P.H. and CAMBRAY, J.A. (1981). The freshwater fishes of the middle and lower Orange River. *Koedoe*, **24**: 5l-66.

SKELTON, P.H., CAMBRAY, J.A., LOMBARD, A. and BENN.A. (1995). Patterns of distribution and conservation status of freshwater fishes in South Africa. *South African Journal of Zoology,* **30**(3): 71-81.

SLINGER J.H. (1988). A mathematical modelling approach to effective flood management of a freshwater wetland and associated pastoral system. CSIR Research Report No. 636. Division of Earth, Marine and Atmospheric Science and Technology, CSIR, Pretoria.

SMUTS, J.C. (1952). *Jan Christian Smuts.* Heinemann and Cassel, Cape Town, South Africa. 568 pages.

SNADDON, C.D., DAVIES, B.R. and WISHART, M.J. (2000). *A Global Overview of Inter-basin Water Transfer Schemes, with an Appraisal of their Ecological, Socio-economic and Socio-Political Implications, and Recommendations for their Management*. WRC Report No. TT 120/00. Water Research Commission, Pretoria, South Africa.

STEIN, E. (1995). Organizational memory: review of concepts and recommendations for management. *International Journal of Information Management*, **15**: 17-32.

TALJAARD, S., ADAMS, J.B., TURPIE, J.K., VAN NIEKERK, L., BATE, G., CYRUS, D., HUIZINGA, P., LAMBERTH, S. and WESTON, B. (2003). *Methodology for the Determination of the Preliminary Ecological Reserve for Estuaries. Version 2*. Department of Water Affairs and Forestry, Pretoria, South Africa.

TALJAARD, S., VAN NIEKERK, L., HUIZINGA, P. and JOUBERT, W. (2003). *Resource Monitoring Procedures for Estuaries for Application in the Ecological Reserve Determination and Implementation Process*. WRC Report No. 1308/1/03. Water Research Commission, Pretoria, South Africa.

TANSLEY, A.G. (1939). *The British Islands and their Vegetation*. Volume 1 of 2. Cambridge University Press, United Kingdom. 484 pages.

TAYLOR, J.C., HARDING, W.R. and ARCHIBALD, C.G.M. (2007a). *A Methods Manual for the Collection, Preparation and Analysis of Diatom Samples. Version 1.0*. WRC Report No. TT 281/07. Water Research Commission, Pretoria, South Africa.

TAYLOR, J.C., HARDING, W.R. and ARCHIBALD, C.G.M. (2007b). *An Illustrated Guide to Some Common Diatom Species from South Africa*. WRC Report No. TT 282/07. Water Research Commission, Pretoria, South Africa.

TEMPELHOFF, J.W.N. (2008). Historical perspectives on pre-colonial irrigation in southern Africa. *African Historical Review*, **40**(1): 121-160.

THARME, R.E. and KING, J.M. (1998). *Development of the Building Block Methodology for Instream Flow Assessments, and Supporting Research on the Effects of Different Magnitude Flows on Riverine Ecosystems*. WRC Report No. 576/1/98. Water Research Commission, Pretoria, South Africa. 452 pages.

TINLEY, K.L. (1964). Fishing methods of the Thonga tribe in north-eastern Zululand and southern Mozambique. *Lammergeyer*, **3**(1): 9-39.

TOERIEN, D.F. (1977). *A Review of Eutrophication and Guidelines for its Control in South Africa*. Report No. WAT48, National Institute for Water Research, CSIR, Pretoria, South Africa.

TOERIEN, D.F., HYMAN, K.L. and BRUWER, M.J. (1975). A preliminary trophic status classification of some South African impoundments. *Water SA*, **1**(1): 15-21.

TOOTH, S., McCARTHY, T.S., BRANDT, D., HANCOX, P.J. and MORRIS, R. (2002). Geological controls on the formation of alluvial meanders and floodplain wetlands: the example of the Klip River, Eastern Free State, South Africa. *Earth Surface Processes and Landforms*, **27**: 797-815.

TURPIE, J.K., ADAMS, J.B., JOUBERT, A., HARRISON, T.D., COLLOTY, B.M., MAREE, R.C., WHITFIELD, A.K., WOOLDRIDGE, T.H., LAMBERTH, S.J, TALJAARD, S. and VAN NIEKERK, L. (2002). Assessment of the conservation priority status of South African estuaries for use in management and water allocation. *Water SA,* **28**(2): 191-206.

TURTON, A.R., ASHTON, P.J. and CLOETE, T.E. (2003). An introduction to the hydropolitical drivers in the Okavango River basin. In: A.R. TURTON, P.J. ASHTON and T.E.

CLOETE (eds), *Transboundary Rivers, Sovereignty and Development: Hydropolitical Drivers in the Okavango River Basin*, Geneva: Green Cross International, Pages 6-30.

TURTON, A.R., EARLE, A., MALZBENDER, D. and ASHTON, P.J. (2005). Hydropolitical vulnerability and resilience along Africa's international waters. In: WOLF, A.T. (Ed.), *Hydropolitical Resilience and Vulnerability along International Waters*. Nairobi: United Nations Environment Program. Report No. UNEP/DEWA/0672/NA. Pages 19-67.

TURTON, A.R. and HENWOOD, R. (Eds) (2002). *Hydropolitics in the Developing World: A Southern African Perspective*. African Water Issues Research Unit (AWIRU), Pretoria, South Africa.

TURTON, A.R., MEISSNER, R., MAMPANE, P.M. and SEREMO, O. (2004). *A Hydropolitical History of South Africa's International River Basins.* WRC Report No. 1220/1/04. Water Research Commission, Pretoria, South Africa.

UNION OF SOUTH AFRICA (1914). Report of the Director of Irrigation for the period 1 January, 1912 to 31 March, 1914. Government Printer, Pretoria, South Africa. Report No: UG2-1914.

UNION OF SOUTH AFRICA (1931). Report of the Director of Irrigation for the period 1 April 1929 to 31 March 1930. Government Printer, Pretoria, South Africa. Report No: UG 13-1931.

UYS, M.C. (Ed.) (1994). *Classification of Rivers and Environmental Health Indicators.* Proceedings of a joint South African / Australian workshop. Cape Town, 7-14 February 1994. WRC Report No. TT 63/94, Water Research Commission, Pretoria, South Africa.

UYS, M.C., GOETSCH, P-A. and O'KEEFFE, J.H. (1996). *National Biomonitoring Programme for Riverine Ecosystems: Ecological indicators, a review and recommendations.* NBP Report Series No. 4. Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria, South Africa.

VAN GINKEL, C.E., GLEN, R.P., GORDON-GRAY, K.D., MUASYA, M. and DEVENTER, P.P. (2011). *Easy Identification of Some South African Wetland Plants*. WRC Report No. TT 479. Water Research Commission, Pretoria.

VAN HUYSSTEEN, C.W., HENSLEY, M., LE ROUX, P.A.L., ZERE, T.B. and DU PREEZ, C.C. (2005). *The Relationship Between Soil Water Regime and Soil Profile Morphology in the Weatherley Catchment, an Afforestation Area in the North Eastern Cape*. WRC Report No. 1317/1/05. Water Research Commission, Pretoria, South Africa.

VAN KERKHOFF, L. and LEBEL, L. (2006). Linking action and knowledge for sustainable development. *Annual Review of Environmental Resources*, **31**: 445-477.

VAN RENSBURG, K.J. (1966). Die vis van die Olifantsrivier (Weskus) met spesiale verwysing na die geelvis *Barbus capensis* en saagvin *Barbus serra*. *Departement Natuurbewaring, Provinsiale Administrasie, Kaap die Goeie Hoop*.

VAN VUUREN, S., TAYLOR, J.C., GERBER, A., VAN GINKEL, C. (2006). *Easy Identification of the Most Common Freshwater Algae*. North-West University and Department of Water Affairs and Forestry, Pretoria, South Africa. 200 pages.

VAN ZINDEREN BAKKER, E.M., WINTERBOTTOM, J.M. and DYER, R.A. (eds) (1971). *Marion and Prince Edward Islands. Report on the South African Biological and Geological Expedition, 1965-1966*. A.A. Balkema, Cape Town, South Africa. 427 pages.

VEGTER, J.R. (2001). *Groundwater Development in South Africa and an Introduction to the Hydrogeology of Groundwater Regions*. WRC Report TT 134/00. Water Research Commission, Pretoria, South Africa.

WAGER, V.A. (1965). *The Frogs of South Africa: Their fascinating life stories.* Delta Books, Johannesburg.

WALMSLEY, R.D. and ASHTON, P.J. (1977). Algal growth potential and the succession of algae in a nitrogen-limited impoundment. *South African Journal of Science*, **73**: 151-152.

WALMSLEY, R.D. and BUTTY, M. (1980). *Limnology of Some Selected South African Impoundments*. Collaborative report by the Water Research Commission and National Institute for Water Research, Pretoria, South Africa.

WALTERS, D.J., KOTZE, D.C. and O'CONNOR, T.G. (2006). Impact of land use on community organization and ecosystem functioning of wetlands in the southern Drakensberg Mountains, South Africa. *Wetlands Ecology and Management*, **14**: 329-348.

WETZEL, R.G. (2003). *Limnology: Lake and River Ecosystems*. Third Edition. Academic Press, San Diego.

WHITFIELD, A.K. (1992). A characterization of southern African estuarine systems. *Southern African Journal of Aquatic Sciences,* **18**(1-2): 89-103.

WHITFIELD, A.K. (1996). A review of estuarine ichthyology in South Africa over the past 50 years. *Transactions of the Royal Society of South Africa*, **51**: 79-89.

WHITFIELD, A.K. (1998). Biology and Ecology of Fishes in Southern African Estuaries. *Ichthyological Monographs of the J.L.B. Smith Institute of Ichthyology*, No. 2, 223 pages.

WHITFIELD, A.K. (2010). A century of fish research in South African estuaries. *African Journal of Aquatic Science*, **35**(3): 211-225.

WILLIAMS, W.D. (1989). *A Statement on the Inland Water Ecosystems Programme and the Current State of Limnology in South Africa*. Confidential contract report, marked "Strictly Confidential", to the Executive of the Foundation for Research Development, Pretoria, South Africa. 25 pages plus 25 pages of appendices.

WOODFORD, D.J. and IMPSON, N.D. (2004). A preliminary assessment of the impact of alien rainbow trout (*Oncorhynchus mykiss*) on indigenous fishes of the upper Berg River, Western Cape Province, South Africa. *African Journal of Aquatic Sciences,* **29**(1): 107-111.

WOODFORD, D.J., IMPSON, N.D., DAY, J.A. and BILLS, I.R. (2005). The predatory impact of invasive alien smallmouth bass, *Micropterus dolomieu* (Teleostei: Centrachidae), on indigenous fish in a Cape Floristic Region mountain stream. *African Journal of Aquatic Sciences,* **30(**2): 167-174.

WRIGHT, J.F., MOSS, D., ARMITAGE, P.D. and FURSE, M.T. (1984). A preliminary classification of running-water sites in Great Britain based on macro-invertebrate species and the prediction of community type using environmental data. *Freshwater Biology,* **14**: 221-256.

ZIMAN, J. (1996). Is science losing its objectivity? *Nature*, **382**: 751-754.

ZOHARY, T. (1985). Hyperscums of the cyanobacterium *Microcystis aeruginosa* in a hypertrophic lake (Hartbeespoort Dam, South Africa). *Journal of Plankton Research*, **7**: 399-409.

ZOHARY, T., JARVIS, A.C., CHUTTER, F.M., ASHTON, P.J. and ROBARTS, R.D. (1988). *The Hartbeespoort Dam Ecosystem Programme, 1980-1988*. Division of Water Technology, CSIR, Pretoria, South Africa. 9 pages.

Appendix A

Record of Regional Meetings

Meeting 1: 23 June 2009, Bloemfontein

Host organisation: Centre for Environmental Studies, University of the Free State
Attendance list:

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Marinda Avenant	avenantmf.sci@ufs.ac.za
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Meeting 2: 9 July 2009, Pretoria

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Meeting 3: 4 August 2009, Grahamstown

Host organisation: South African Institute for Aquatic Biodiversity
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Meeting 4: 19 August 2009, Pietermaritzburg

Host organisation: Centre for Environment, Agriculture and Development, University of KwaZulu-Natal, Pietermaritzburg
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Meeting 5: 31 August 2009, Cape Town

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Sue Matthews	

Appendix B

Names and contact details of the aquatic scientists who were contacted at the start of this project

(**Note**: Unfortunately, several of the contact details listed below are now out of date).

(The abbreviations for provinces are as follows: EC = Eastern Cape; FS = Free State; G = Gauteng; KZN = KwaZulu-Natal; LP = Limpopo; MP = Mpumalanga; NW = North West; WC = Western Cape).

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Appendix C

History of the Hydrological Research Institute

Speech delivered on the occasion of the Institute's 21st anniversary in 1993 by Joan S. Whitmore [1922-2002]
(Joan Whitmore was the first director, 1970-1977).
(Source: http://www.dwaf.gov.za/iwqs/iwqshistory/hristory.asp)

Against the tranquil backdrop of Roodeplaat Dam and the surrounding hills, the Hydrological Research Institute was the scene of unusual animation, activity and anticipation on 20th October 1972 in preparation for the official opening ceremony that afternoon. In front of the building the Public Works Department had erected a sturdy platform decked with the Department of Water Affair's logo and set out lorry loads of chairs. It also brought masses of colourful pot-plants with which to decorate the foyer, the corridors and main offices. The commemorative plaque was mounted at the entrance, and I duly checked that when the Minister pulled the cord to unveil it, the velvet curtain would slide back smoothly. Meanwhile the staff mounted exhibits and posters, and prepared the refreshments. We'd thought of every contingency except one, the unusual heat – but in answer to an urgent appeal at the Minister's behest, a Coca Cola van raced up an hour before the proceedings commenced, with a load of red and white sun umbrellas. Then a stream of cars arrived, bringing representatives of many Departments and organizations with an interest in water. The guests sought shelter under the sun umbrellas and the Ministerial party mounted the platform, the ladies wearing hats and gloves as befitted those times and the formality of the occasion. The Rev. WB Jansen opened the proceedings with scripture reading and prayer, whereupon I, as the Director of the Institute welcomed the guests. The Secretary for Water Affairs, Mr JP Kriel, introduced the Minister, the Hon. SP (Fanie) Botha who, after delivering an address, unveiled the plaque, whereupon the Chief of Scientific Services, Dr PW de Lange, thanked one and all. The staff then conducted the guests on a tour of the Institute and served them refreshments.

And now I should like to tell you how all this began, and why.

As you all well know, it is because South Africa's water supplies are at best undependable, and at worst grossly inadequate, that they are infinitely more precious than our much vaunted gold – for they are vital not only to all sectors of our economy but to our very survival and that of every plant and creature. Small wonder therefore that South Africa has a long and creditable history of water research and development. I recall hearing vivid accounts by the late Dr MS du Toit, an eminent soil scientist who later became Secretary for Agriculture, of his arduous trips by donkey cart and mule wagon to lay out the Olifants River and other early irrigation schemes in the Western Cape Province. In another sphere the late Prof. CL Wicht put forest hydrology on the world map with his catchment experiments at Jonkershoek on the effects of afforestation and forest management on stream flow, in which he was a pioneer in the statistical design and evaluation of controlled catchment Experiments. We can also look back with admiration on the construction, largely by manual labour, of the Vaal-Hartz Irrigation Scheme, a major scheme by any standards, which was undertaken primarily to give employment to many of those hit by the great depression of the early '30's. That the entire scheme was completed without provision of drainage canals for the return flow was certainly an oversight but one which could be remedied later and which did not detract from the magnitude of the achievement at a time of acute economic recession. And later came bold and imaginative schemes in yet another sphere, that of large-scale transfer of surplus water from some catchments to make good deficiencies in others, the Tugela-Vaal and Orange-Fish being two major examples. And when the need arose to start thinking of desalinating and reusing water, Dr Stander of the CSIR earned world recognition.

It seems to me that during the first 60 years of this century we relied more on the vision, initiative and drive of gifted individuals, than on the corporate style of management via a plethora of committees, which is so prevalent today.

The years following World War II saw an explosive proliferation of research on the occurrence and use of water in many State Departments and Universities. Thus the Weather Bureau not only expanded its rain gauge network but also moved towards greater automation. The Department of Agriculture intensified its research on not only the chemical but also the physical (especially moisture) characteristics of soil types, also on crop water requirements and water use efficiency in relation to planting date and density, fertilizer treatment and other variables, and on irrigation scheduling. The Departments of Agriculture and of Forestry as well as various universities increased the number of controlled catchment experiments (often maintaining independent flow-gauging and weather stations). The Department of Water Affairs likewise expanded its network of hydrometric stations, gradually substituting automatic recorders for visual observations: it also maintained a network of rainfall and evaporation stations independently of the Weather Bureau, and like the Geological Survey also operated a network of groundwater stations.

The foregoing indicates that although there was much activity across a broad spectrum of hydrological research, it was fragmented. Not only was there considerable overlap and duplication of effort (and expenditure) but some fields of research suffered neglect, and there was undue competition for scarce staff and funding.

An interdepartmental commission appointed to address these problems recognized the need for specialized research to continue in various departments but recommended:

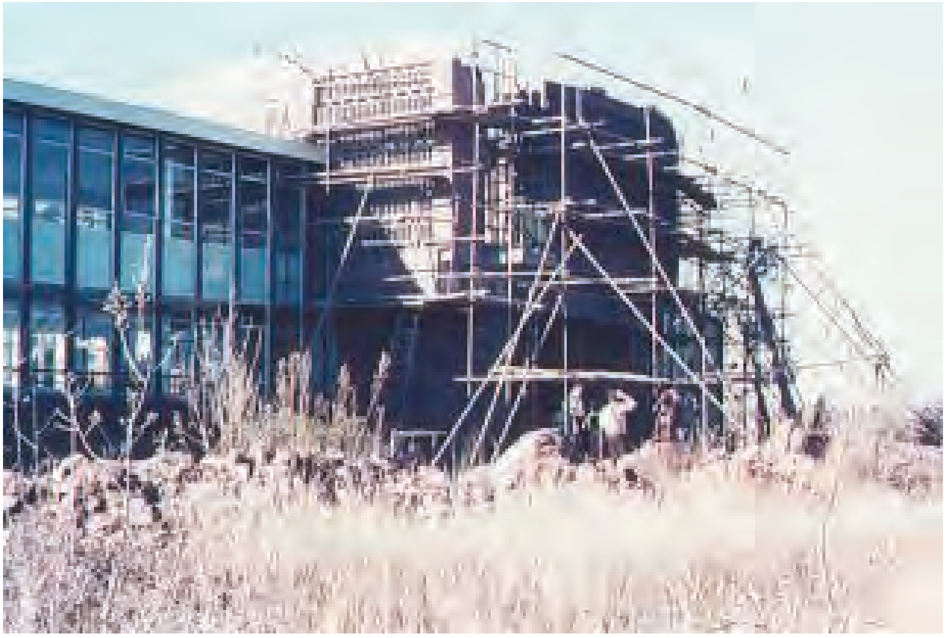
- The appointment of an Interdepartmental Coordinating Committee for Hydrological Research; and
- The creation of a focal point in the form of a central Division of Hydrological Research within an existing department, to give a lead and impetus to hydrological research as a whole, to initiate new research, amplify work already in progress and eliminate gaps in the field.

The merits of attaching that new division to the Department of Water Affairs (then the Department of Irrigation) are debatable, firstly because the department had not itself felt the need for such a division which was virtually foisted upon it, and secondly because the department was not research-oriented, its main function having been to construct and administer dams, and thirdly because it had only engineers, not scientists on its professional staff. Be that as it may, the new division of Hydrological Research was established in 1958, with a departmental engineer, Mr TC Menne as its Director, and another engineer, Mr JP Kriel, as one of the two Assistant Directors, the other members of the nucleus of staff being drawn from other departments such as the Department of Mines (Dr J Enslin), Transport (Mr K Harvey) and Agriculture (myself).

For all that the Interdepartmental Commission had recommended the creation of a Division of Hydrological RESEARCH, the Commission had failed to make any mention of research facilities. All we had to work with were the valuable accumulated hydrometric records of stream flow, dams and boreholes. A lot could be extracted from them, my first breakthrough coming when I could prove by covariance and other statistical techniques that the reduced inflow into certain dams and the increasingly frequent need to cut water quotas was not due solely to drought as had been assumed but to the effects on runoff of changed land management upstream in the catchments. Initially, though not for long, scientists and engineers were paid the same salary, and so were men and women on the professional staff. This gave us an edge in recruitment over other departments, enabling us to recruit staff in droves only to lose them again in droves a few months later for lack of research facilities. After losing much sleep over this problem the light dawned at 3:00 one morning: Of course we needed to build a research institute, big enough to accommodate the many facets of hydrological research needing attention, and the best of its kind in the world!! A simple and obvious solution – but how to set about it?

As a newcomer, relatively junior, a non-engineer, and the only woman on the professional staff, the odds were weighted heavily against me. Instinctively I knew that if I followed the prescribed "bottom-up" approach I probably wouldn't get more than two rungs up the hierarchical ladder of consent before the scheme would be firmly, finally and irrevocably quashed. So with a blend of zealous and unquenchable fervour and naivety I decided that my only workable option was to start at the top and try to secure the approval of the head of the department, Mr JM Jordaan, for my idea. Knowing that he came to office at 7:00 in the morning I was already waiting in the anteroom when he arrived. I put my case, and five minutes later floated out on a cloud of jubilation, having obtained his enthusiastic approval in principle. "I can already see the name over the gate" he said. And that's when my troubles began in earnest, for naturally I had antagonized many people in the Department by going over their heads. But I was not unduly conscience-stricken, having acted not out of self-interest but from the utter conviction that the Department and the country truly and urgently needed a research institute – but paid the penalty in the form of six lonely years of fighting for that conviction. I wrote countless submission and memoranda based on solid facts and arguments – but not neglecting to add on occasion that the head of the Department supported the idea. Within the Department I had to convince the Staff Committee, the Planning Committee, the Finance Committee and several others, not to mention the Interdepartmental Co-ordinating Committee for Hydrological Research, the Public Service Commission, the Treasury, the Public Works Department, and so on. Such was the opposition I sometimes encountered that often in the dark hours of the night I wondered "Is it possible that everyone else is wrong and only you are right?" But I had a few supporters notably Mr Menne, the head of the Division, who selected the rock outcrop on which the Institute is sited, the Chief Accountant, Mr Bekker, who caught my vision, and the Circle Engineer, Mr JC Cox who helped in countless ways with the water supply, the fencing and other practical matters once the Institute had been erected within his domain.

But my troubles were far from being at an end. Without having visited the site, the architect produced a plan of a concrete box of a building which would have blended well with countless other similar boxes in a modern concrete city, but would have desecrated the beautiful virgin terrain where the Institute was to be erected. Our views were so divergent that finally we drove through Pretoria looking for any building styles or features that were acceptable to both of us – and fortunately we found common ground in the architecture of Norman Eaton. Thus the columnar brickwork of the facade is a feature culled from the wall he designed around a church. Some irreversible mistakes occurred. Thus I had not realized from the plans that the windows in some laboratories were inconveniently high. Also I had wanted the stone foundation to be rough and craggy so as to harmonize with the surrounding rocks and was dismayed to find one morning that the Italian stonemasons had set the stones in a smooth jigsaw pattern before I could intervene. To crown it all, the builder went bankrupt before he had completed the building. The daunting thought occurred to me that if Winston Churchill could take up bricklaying, maybe so should I in order to finish the building project – but the Public Works Department re-awarded the contract, and finally after all these frustrating setbacks and delays, the building was ready for occupation in 1970.



In designing the Institute I wanted to profit from the experience of others – but as most hydrological research units have been part of existing engineering department, I wrote to a wide range of other research organizations worldwide, asking the basic question: "*Based on your experience since the inception of your institute, what mistakes would you be careful to avoid if you had to start again?*" Two items of advice stood out: Firstly – build a structure far larger than is required for present requirements and those envisaged for the near future. In this I was thwarted by the Public Works Department's design regulations of *x* square metres per person, plus *y*%, which allowed for only modest, that is, short-term growth. The best way I saw of overcoming this restriction was to make it possible to build extensions at the ends of each wing and transverse corridor – a facility which has since proved its worth. Secondly – build for flexibility, for in a new, broad, innovative and rapidly developing field of research such as hydrology you have no inkling of what you will be engaged upon ten years hence. If you fail to build an adaptable structure it may well be outmoded and redundant not long after completion. This provision for changing and expanding needs I tried to achieve by extensive use of demountable interior walls, enabling the number, size, shape and use of rooms to be altered at will at only modest expense and inconvenience. But the price of this versatility was some loss of privacy, for the partitions were far from soundproof.

I have dwelt on the events which led to the founding of the Hydrological Research Institute (herein after referred to as the HRI), and on its design philosophy – but what of the work for which the HRI was intended? It was clearly the view of the 'founding fathers' – the Interdepartmental Commission which, to counter the growing fragmentation of hydrological research, recommended the establishment of a central, unifying division of hydrological research – that hydrology was, and should be nurtured as, a HOLISTIC science. This is a view I still uphold. At the risk of being trite, let me repeat what is well-known but tends to be overlooked – that our planet's water resources, dating back to its creation, are substantially fixed but are both highly mobile and subject to constant changes in form between the gaseous (water vapour), liquid (water) and solid (ice) forms. Interacting powerfully with other substances, our water resources are also highly variable and sensitive as regards quality. In effect, the many hydrological processes are intricately *interrelated*, with the result that a change in any one has a chain-reaction on others, often with far-reaching consequences. Thus even common practices such as burning large expanses of veld or ploughing them and planting mielies alter the quantity, time disposition and quality of runoff, base flow, and groundwater accrual, not to mention the quantity and quality of water reaching users downstream. More often than not these changes, sometimes damaging, occur inadvertently and may be difficult to remedy – but they could have been *anticipated* by the foreknowledge whose acquisition is the task of the hydrological researcher. But such foreknowledge also enables us to *manipulate* hydrological processes beneficially, one example being mulching to curb unproductive evaporation of soil moisture, so as to make more available for assimilation and thus the growth and yield of crops. Cloud seeding, again, is an example of an intervention with potential for both harm and good.

Consequently the HRI initially comprised seven sections viz.:

1. **Hydrometeorology**: The atmosphere being regarded as the primary renewable source of fresh water, the section studied, inter alia, changes in the intensity / frequency distribution of rainfall, runs of wet and dry years, the incidence and classification of drought, prediction of the mean annual rainfall of uncaused catchments based on altitude and locality factors, the feasibility of extracting water from cloud caps on mountains, and evaporation suppression, and also collaborated with the Weather Bureau in a study of the hydrological consequences of rainfall stimulation.
2. **Surface water hydrology**: This section initiated some of the earliest attempts in South Africa in computer modelling of river flow, and undertook studies of seiches and the propagation of density currents in dams, of the transport and deposition of sediments, and of estimating and reducing evaporation from dams.
3. **Groundwater hydrology**: In addition to studies on the natural and artificial recharge of aquifers, the use of radioactive and stable isotopes and other techniques for studying groundwater recharge, movement, yield and age, and even the use of explosives to increase borehole yields, many ad hoc investigations were conducted in various parts of the country.
4. **Water Quality**: Anticipating the growing threat of water pollution despite enlightened water legislation aimed at prevention rather than cure, the HRI initiated an extensive preliminary limnological survey of all major fresh water bodies in South Africa, and was also one of the first to acquire an Auto-analyser to automate and so speed up the analysis of the rapidly increasing number of water samples. It transpired that the instrument had been designed primarily for use in the medical sphere, so many adjustments and recalibrations had to be made. Biological studies of water and sediments also commenced.

5. **Catchment Management**: The work of this section centred mainly on statistical analysis of meteorological and hydrometric records to discern trends in unit runoff and flow characteristics, and by linking these to successive aerial and ground surveys to interpret the trends in terms of discernible changes in land use.
6. **Hydrological Techniques**: This section concentrated on testing and developing new research techniques such as the use of isotopes, simulation modelling, evaporation measurement and estimation, water sampling etc., which could then be used by other sections in their specific investigations.
7. **Multi-disciplinary Research**: The main function of this section was to liaise with bodies such as the Geological Survey, the Weather Bureau, the Department of Agriculture and of Forestry, the CSIR, and various universities on joint research and other matters of common concern. It also functioned as the secretariat of the Interdepartmental Committee for Hydrological Research.
8.

It is questionable whether any organization ever achieves its full potential. That is certainly true of the HRI, for it encountered many problems.

For one thing, at its inception there was no formal, comprehensive training for hydrologists available in South Africa except for the courses included in the curricula of some engineering faculties. Instead we had to recruit staff from a range of scientific disciplines such as mathematics, geology, geography, physics, chemistry, botany and zoology, some of which had only tenuous links with water. Moreover, as it was a period when there were more attractive openings in the private sector, we had to employ whom we could get rather than what we needed to implement our research blueprint. (For example, at one stage there was a surfeit of nuclear physicists). Inevitably this led to some imbalances and gaps in the staff structure and research progress. But on the positive side there was a lot of cross-fertilization of ideas and expertise, and at one stage there were no fewer than eight nationalities among the staff. Moreover, on occasion graduate students from the University of Aberystwyth and from Germany spent some months at the HRI, assisting in projects and gaining experience.

The second but perhaps the major drawback was that, by nature and by training, relatively few scientists, then or now, are able to think holistically – and as I have emphasised, hydrology with its multiplicity of finely balanced interactions is a holistic science. Perhaps the problem arose from our education system which requires students to start specialising early on, causing a student's sphere of knowledge to become ever narrower and more concentrated, whereas a hydrologist needs to comprehend an ever broader spectrum. It is a transformation of thought process that many are unable, or disinclined, to achieve. Speaking personally I count it a singular privilege and advantage to have taken a hybrid degree with an almost equal balance of arts and science subjects, for I think that the sciences lend precision to the arts which, in turn, impart vision to the sciences. Perhaps the science and philosophy of ecology has progressed further than hydrology in promoting the holistic approach – and there are some tentative signs that this may also be starting to develop in medicine.

Thirdly we had to contend with piracy. The HRI proved to be a good recruiting outfit, and once they had proved their merit, the most promising staff were sometimes transferred to other divisions within the Department, who had been less successful in the recruitment race. This dubious practice climaxed when, after a gruelling Public Service inspection, two posts of Assistant Director were created for the HRI – whereupon head office promptly filched them both to promote and retain engineers elsewhere in the country, leaving me, as Director to continue carrying the acknowledged workload of three people.

And fourthly the swing of the pendulum between centralization and decentralization, between aggregation and segregation, which for so long has been characteristic of the Public Service, continued, and has probably not yet ceased. A growing organization almost inevitably tends to be split up – as for example, when geohydrological research hived off as a separate entity. And fifthly, research emphasis inevitably shifts with changing needs. This is right and natural – provided it does not become too narrow and inflexible, or deprive other research fields of the attention they merit.

That the HRI has survived for 21 years suggests that it has indeed met a need, and is a tribute to the dedication of its staff. It has come a long way since it was officially opened on 20 October 1972, its achievements based on satellite imagery being but one of the exciting new developments never envisaged at that time. I wish to congratulate you one and all, and to wish you continued success in confronting the mounting challenges of the future.

Appendix D

List of published papers provided by contributors that were not cited in the main report

ACREMAN, M. and KING, J.M. (2003). Defining water requirements. Chapter 2 (pages 11-30), in: M. DYSON, G. BERGKAMP and J. SCANLON (eds), *FLOW: The Essentials of Environmental Flows*. IUCN, Gland, Switzerland and Cambridge.

BLOOMER, P. and IMPSON, N.D. (2000). Mitochondrial DNA differentiation in the critically endangered Berg River redfin *Pseudobarbus burgi*. *Journal of Heredity,* **91**: 122-127.

BOK, A. H. and IMMELMAN, P.P. (1989). Natural and induced spawning of whitefish, *Barbus andrewi*. *South African Journal of Wildlife Research*, **1**: 1-3.

BROWN, C.A. and KING, J.M. (2006). Implications of upstream water uses on downstream ecosystems and livelihoods. *International Journal of Ecology and Environmental Sciences,* **32**(1): 99-108.

BROWN, C., PEMBERTON, C., BIRKHEAD, A., BOK, A, BOUCHER, C., DOLLAR, E., HARDING, W.R., KAMISH, W., KING, J.M., PAXTON, B. and RACTLIFFE, S. (2006). In support of water resource planning – highlighting key management issues using DRIFT: A case study. *Water SA,* **32**: 181-191.

CAMBRAY, J.A. and JUBB, R. (1977). Dispersal of fishes via the Orange-Fish Tunnel, South Africa. *Journal of the Limnological Society of southern Africa*, **3**: 33-35.

CODD, G.A., AZEVEDO, S.M.F.O., BAGCHI, S.N., BURCH, M.D., CARMICHAEL, W.W., HARDING, W.R., KAYA, K. and UTKILEN, H.C. (2005). *CYANONET: A Global Network for Cyanobacterial Bloom and Toxin Risk Management*. UNESCO International Hydrological Programme. IHP-VI Technical Documents in Hydrology 76.

DAVIES, B.R. and WISHART, M.J. (2000). River conservation in the countries of the Southern African Development Community (SADC). In: P.J. BOON, B.R. DAVIES and G.E. PETTS (eds), *Global Perspectives on River Conservation: Science, Policy and Practice*. John Wiley and Sons Ltd., Chichester, England. Pages 179-204.

DE MOOR, F.C. (2002). Shortcomings and advantages of using rapid biological assessment techniques for determining the health of rivers in South Africa. *Verhandlungen Internationale Vereinigung Limnologicae,* **28:** 651-662.

DE MOOR F.C. (2007). Regional biogeographical differences in Trichoptera diversity in South Africa: Observed patterns and processes. In: J. BUENO-SORIA, R. BARBA-ALVARES and B. ARMITAGE (eds), *Proceedings of the 12th International Symposium on Trichoptera. (2006 Mexico City).* The Caddis Press. Pages 211-218.

DE MOOR, F.C. and BELLINGAN T.A. (2010). A survey of macroinvertebrate diversity of eleven rivers in and around the Tsitsikamma National Park, Eastern Cape, South Africa. Final Report for the Tsitsikamma Steering Committee, Nature's Valley, South Africa.

DICKENS, C.W.S., GRAHAM, P.M., SEKWELE, R., MacFARLANE, D.M. and PRINGLE, K. (2008). *Quality Assurance for the National Aquatic Ecosystems Health Monitoring Programme (RHP).* RQS, Department of Water Affairs and Forestry, Pretoria, South Africa.

EEKHOUT, S., KING, J.M. and WACKERNAGEL, A. (1997). *Classification of South African Rivers*. 2 Volumes. Department of Environment Affairs and Tourism, Pretoria, South Africa.

GORDON-GRAY, K.D., WARD, C.J. and EDWARDS, T.J. (2006). Studies in Cyperaceae in southern Africa 38: The identities of *Cyperus natalensis, Cyperus crassipes* and *Cyperus brevis. South African Journal of Botany,* **72**: 133-138.

GORE, J.A., KING, J.M. and HAMMAN, K.C.D (1991). Application of the instream flow incremental methodology to southern African rivers: Protecting endemic fish of the Olifants River. *Water SA*, **17**(3): 225-236.

GWRC (Global Water Research Coalition) (2009) Hazard Identification and Risk Assessment in Source Waters. In: G. NEWCOMBE (Ed.), *International Guidance Manual for the Management of Toxic Cyanobacteria*. Global Water Research Coalition, London. Available (online) at:
http:// www.globalwaterresearch coalition.net

HAMMAN, K., CAMBRAY, J.A., BOUCHER, C. and ROURKE, J. (1991). The Olifants River gorge: one of South Africa's natural wonders. *African Wildlife*, **45**: 116-120.

HARDING, W.R. (1991). *The Ecology of Some Urban-impacted Coastal Vleis on the Cape Flats Near Cape Town, With Special Reference to Phytoplankton Periodicity*. Unpublished MSc Thesis, University of Cape Town, Cape Town, South Africa.

HARDING, W.R. (1992a). A Contribution to the knowledge of South African coastal vleis: The limnology and phytoplankton periodicity of Princess Vlei, Cape Peninsula. *Water SA,* **18**(2): 121-130.

HARDING, W.R. (1992b). Zeekoevlei – Water chemistry and phytoplankton periodicity. *Water SA,* **18**(4): 237-246.

HARDING, W.R. (1993). Faecal coliform densities and water quality in three coastal recreational lakes in the SW Cape, South Africa. *Water SA,* **19**(3): 235-246.

HARDING, W.R. (1994). Water quality trends and the influence of salinity in a highly regulated estuary near Cape Town, South Africa*. South African Journal of Science,* **90**: 240-246.

HARDING, W.R. (1997a). Phytoplankton primary production in a shallow, well-mixed, hypertrophic South African lake. *Hydrobiologia*, **344**: 87-102.

HARDING, W.R. (1997b). South Africa. New regional emergence of cyanobacterial toxicosis. IOC *Harmful Algal News,* **16**: 12-13.

HARDING, W.R. (1997c) Rivers – Arteries of the Earth: A South African Experience. *LakeLine,* **17**(2):18-19.

HARDING, W.R. (1999). Saving a wetland and marine mussel resource impacted by cyanobacterial hepatotoxins. IOC *Harmful Algal News,* **18**: 11.

HARDING, W.R. (2000). Eradication of a freshwater cyanobacterial (*Microcystis aeruginosa*) bloom, causing accumulation of hepatotoxins in marine filter feeders (*Choromytilus meridionalis* and *Mytilus galloprovincialis*), using artificial salinity enhancement. *Verhandlungen Internationale Vereinigung Limnologicae,* **27**: 2120-2123.

HARDING, W.R. (2006). *A Research Strategy for the Detection and Management of Algal Toxins in Water Sources*. WRC Report No. TT 277/06. Water Research Commission, Pretoria, South Africa.

HARDING, W.R., ARCHIBALD, C.G.M. and TAYLOR, J.C. (2005). The relevance of diatoms for water quality assessment in South Africa: A position paper. *Water SA,* **31**: 41-46.

HARDING, W.R., DOWNING, T.G., VAN GINKEL, C.E. and MOOLMAN, A.P.M. (2009). Cyanobacterial research and management in South Africa post-2000. *Water SA,* **35**: 479-484.

HARDING, W.R. and PAXTON, B.A. (2002). Cyanobacteria in South Africa: A Review. WRC Report No. TT 153/01. Water Research Commission, Pretoria, South Africa.

HARDING, W.R., PEROLD, S.M. and GLEN, R.P. (2000). Hepaticae and Zannichelliaceae. New records from an ephemeral pan, Blouvlei, in Western Cape, South Africa. *Bothalia,* **30**: 157-159.

HARDING, W.R., ROWE, N., WESSELS, J.C., BEATTIE, K.A. and CODD, G.A. (1995). Animal toxicosis attributed to the cyanobacterial (blue-green algal) hepatotoxin nodularin at a hypertrophic South African lake. *Journal of the South African Veterinary Association,* **66**(4): 256-259.

HARDING, W.R. and WRIGHT, S. (1999). Initial findings regarding changes in phyto- and zooplankton composition and abundance following the temporary drawdown and refilling of a shallow, hypertophic South African coastal lake. *Journal of Lake and Reservoir Management,* **15**(1): 47-53.

HART, R.C. (1976). The substrate bin – a new sampling device for studying diel vertical migratory movements on to and off lake sediments. *Freshwater Biology,* **6**: 155-159.

HART, R.C. (1981b). Population dynamics and demography of an estuarine copepod (*Pseudodiaptomus hessei*) in Lake Sibaya, a subtropical freshwater coastal lake. *Journal of the Limnological Society of southern Africa,* **7**: 13-23.

HART, R.C. (1984). Zooplankton community grazing in silt-laden Lake le Roux, Orange River, South Africa. *Verhandlungen internationale Vereinigung für theoretische und angewandte Limnologie,* **22**: 1602-1607.

HART, R.C. (1986a). Zooplankton abundance, community structure and dynamics in relation to inorganic turbidity, and their implications for a potential fishery in subtropical Lake le Roux, South Africa. *Freshwater Biology,* **16**: 351-371.

HART, R.C. (1986b). Aspects of the feeding ecology of turbid water zooplankton. *In situ* studies of community filtration rates in silt-laden Lake le Roux, Orange River, South Africa. *Journal of Plankton Research,* **8**: 401-426.

HART, R.C. (1987a). Observations on calanoid diet, seston, phytoplankton-zooplankton relationships, and inferences on calanoid food limitation in a silt laden reservoir. *Archiv für Hydrobiologie,* **111**: 67-82.

HART, R.C. (1987b). Population dynamics and production of five crustacean zooplankters in a subtropical reservoir during years of contrasting turbidity. *Freshwater Biology,* **18**: 287-318.

HART, R.C. (1988). Zooplankton feeding rates in relation to suspended sediment content: potential influences on community structure in a turbid reservoir. *Freshwater Biology,* **19**: 123-139.

HART, R.C. (1990a). Zooplankton distribution in relation to turbidity and related environmental gradients in a large subtropical reservoir: patterns and implications. *Freshwater Biology,* **24**: 241-263.

HART, R.C. (1990b). Copepod post-embryonic durations: pattern, conformity, and predictability. The realities of isochronal and equiproportional development, and trends in copepodid-naupliar duration ratio. *Hydrobiologia,* **206**: 175-206.

HART, R.C. (1992a). Experimental studies on food and suspended sediment effects on growth and reproduction of six planktonic cladocerans. *Journal of Plankton Research,* **14**: 1425-1448.

HART, R.C. (1992b). Aspects of comparative plankton ecology in cascading Mgeni River reservoirs (Midmar, Albert Falls, and Nagle): an overview. *Southern African Journal of Aquatic Science,* **18**: 20-41.

HART, R.C. (1994a). Equiproportional temperature-duration responses and thermal influences on distribution and species switching in the copepods *Metadiaptomus meridianus* and *Tropodiaptomus spectabilis. Hydrobiologia,* **272**: 163-183.

HART, R.C. and ALLANSON, B.R. (1981). Energy requirements of the tropical freshwater shrimp *Caridina nilotica* (Decapoda: Atyidae). *Verhandlungen internationale Vereinigung für theoretische und angewandte Limnologie*, **21**: 1597-1602.

HEEG, J. and BREEN, C.M. (1994). Resolution of conflicting values on the Pongolo River Floodplain (South Africa). In: B. PATTEN, S. JÖRGENSON and H. DUMONT (eds), *Wetlands and Shallow Continental Water Bodies*, Volume 2. SBP Publishing, The Hague, The Netherlands. Pages 303-359.

IMPSON, N.D. (1994). The role of Cape Nature Conservation in regulating the importation and culture of exotic ornamental freshwater fish species in the Cape Province. In: P.J. BRITS and S. DE KOCK (eds), *The South African Ornamental Fish Trade*. *Proceedings of the Annual Conference of the South African Association of Aquatic Scientists, 3.* 48 pages.

IMPSON, N.D. (1996). National aquarist body key to keeping indigenous fish. *South African Fishkeeping* 1 (6): 11.

IMPSON, N.D. (2000a). Environmentally friendly fishing: a buzzword or fishing hand-in-hand with nature? *Flyfishing,* **60**: 60-61.

IMPSON, N.D. (2000b). How many yellowfishes have you caught? Seven down, two to go. *Flyfishing,* **61**: 28-31.

IMPSON, N.D. (2001a). When yellowfish become an invasive species – mistakes of the past. *Piscator,* **133**: 28-37.

IMPSON, N.D. (2001b). Why the Salt River at the Crags (southern Cape region) should not be stocked with fish. *Piscator,* **133**: 59-63.

IMPSON, N.D. (2001c). Sawfin – our most threatened yellowfish. *Flyfishing,* **64**: 21-23.

IMPSON, N.D. (2002). Flyfishing and Environmental Conservation. In: L. WOLHUTER (Ed.), *The Nedbank Guide to Flyfishing in southern Africa*. Pages 366-372.

IMPSON, N.D. (2003). A lesson too late for the learning. Berg River whitefish now extinct. *Flyfishing,* **79**: 29-31.

IMPSON, N.D. (2004a). Research confirms severe impacts of smallmouth bass on indigenous fishes in Western Cape. *SA Bassing*, December 2004.

IMPSON, N.D. (2004b). The threatened yellowfishes of Western Cape. In: L. WOLHUTER (Ed.), *The Nedbank Guide to Flyfishing in Southern Africa*. pages 217-222.

IMPSON, N.D and Woodford, D. (2005). Alien invaders: guilty. Just how bad are smallmouth bass for Cape rivers? *Flyfishing,* **88**: 32-33.

IMPSON, N.D. (2006). Importance of riparian zones. *Flyfishing* 90.

IMPSON, N.D. (2007a). Rotenone as a tool for restoring indigenous fishes and inland waters. *Piscator*, **139**: 4-9.

IMPSON, N.D. (2007b). Freshwater fishes. In: *Western Cape State of Biodiversity Report 2007*, Scientific Services, CapeNature. pp. 18-35.

IMPSON, N.D. (2007c). Stocking yellowfishes for recreation and conservation. In: L. WOLHUTER and N.D. IMPSON (eds), *The State of Yellowfishes in South Africa 2007*. Water Research Commission, Pretoria, South Africa. pp. 60-61.

IMPSON, N.D. (2008a). Status of the Clanwilliam yellowfish. In:. N.D. IMPSON, I.R. BILLS and l. WOLHUTER (eds), *National Status of Yellowfish in South Africa 2007*. Water Research Commission, Pretoria, South Africa.

IMPSON, N.D. (2008b). Status of the Berg-Breede whitefish. In:. N.D. IMPSON, I.R. BILLS and L. WOLHUTER (eds), *National Status of Yellowfish in South Africa 2007*. Water Research Commission, Pretoria, South Africa.

IMPSON, N.D. (2008c). Yes, there is a future for trout in South Africa. *Flyfishing*, **92**.

IMPSON, N.D. (2009a). Invasive alien freshwater fishes in South Africa: a mixed blessing? *African Wildlife*, **63**(1).

IMPSON, N.D. (2009b). Hex River bulldozing. Unique fish community threatened. *African Wildlife*, **63(**2): 30-31.

IMPSON, N.D., ABRAHAMS, A and TURNER, A. (2003). Freshwater fishes of the Succulent Karoo Biome: Distribution, conservation status, hotspots and associated conservation issues. In: A. DRIVER, P. DESMET, M. ROUGET, R.M. COWLING and K. MAZE (eds), *Succulent Karoo Ecosystem Plan: Biodiversity Component Technical Report*. Appendix 4. Cape Conservation Unit Report No CCU 1/03, Botanical Society of South Africa.

IMPSON, N.D., BILLS, I.R. and CAMBRAY, J.A. (2002a). A conservation plan for the unique and highly threatened freshwater fishes of the Cape Floral Kingdom. In: M.J. COLLARES-PEREIRA, I.G. COWX and M.M. COELHO (eds), *Conservation of Freshwater Fishes: Options for the future*. Blackwell Science, London, pp 432-442.

IMPSON, N.D., BILLS, I.R. and CAMBRAY, J.A. (2002b). State of Biodiversity, Western Cape, South Africa: Freshwater Fishes. In: *Biodiversity of the Western Cape 2002*, 13 pp. Obtainable from: www.capenature.org.za

IMPSON, N.D., BILLS, I.R., CAMBRAY, J.A. and LE ROUX, A. (1999). The primary freshwater fishes of the Cape Floristic Region: conservation needs for a unique and highly threatened fauna. Cape Nature Conservation Report to the University of Cape Town for the CAPE analysis. 26 pages.

IMPSON, N.D. and BLOOMER, P. (1998/1999). Genetic variation between four whitefish (*Barbus andrewi*) populations and implications for management. *South African Journal of Aquatic Science,* **24**(1/2): 2-10.

IMPSON, N.D. and HAMMAN, K.C.D. (2000). Conservation status, threats and future prospects for the survival of the freshwater fishes of the Western Cape Province, South Africa. In: I. COWX (Ed.), *Proceedings of the Conference on the Management and Ecology of River Fisheries*. Blackwell Science, London, pages 418-427.

IMPSON, D., HARDING, W.R. and STEYN, G. (2005). The use of rotenone as a tool for restructuring fish populations in inland waters of the fynbos biome. *Piscator,* **137**: 63-69

IMPSON, N.D., HERDIEN, E and BELCHER, A. (2007). Status of River Health. In: *Western Cape State of Biodiversity Report 2007*. Scientific Services, CapeNature, South Africa. Pages 159-174.

IMPSON, N.D., MARRIOTT, M.R., BILLS, I.R. and SKELTON, P.H. (2007). Conservation biology and management of a critically endangered cyprinid, the Twee River redfin, *Barbus erubescens* (Teleostei: Cyprinidae), of the Cape Floristic Region, South Africa. *African Journal of Aquatic Science*, **32**.

IMPSON, N.D and MINCHER, B. (2008). Living Gold: Status and importance of South Africa's yellowfishes. 16th Vision Annual. Endangered Wildlife Trust, Johannesburg, South Africa. Pages 76-79.

IMPSON, D. and THARME, R. (1998). Translocation of indigenous freshwater fishes for conservation and flyfishing: the Boontjies River, Western Cape, as a case study. *Piscator,* **130**: 87-92.

KING, J.M., CAMBRAY, J.A. and IMPSON, N.D. (1998). Linked effects of dam-released floods and water temperature on spawning of the Clanwilliam yellowfish *Barbus capensis. Hydrobiologia,* **384**: 245-265.

MOUTON, A., BASSON, L. and IMPSON, N.D. (2001). Health status of ornamental freshwater fishes imported to South Africa: a pilot study. *Aquarium Sciences and Conservation,* **3**: 327-333.

MUCINA, L. and RUTHERFORD, M.C. (2006). Vegetation of South Africa, Lesotho and Swaziland. *Strelizia,* **19**: 1-808.

O'KEEFFE, J.H., ASHTON, P.J., BRINK, P., BRUWER, C.A., ENGELBRECHT, J., HAMMAN, K., KING, J.M, KLEYNHANS, C.J., PORTER, R., SKELTON, P. and VAN LOGGERENBERG, N. (1987). A national classification system for rivers. In: *Proceedings of a Workshop on River Classification, held at Lydenburg, Transvaal*. Foundation for Research Development, Pretoria, South Africa. 20 pages.

O'KEEFFE, J.H., KING, J.M., DAY, J.A., ROUSSOUW, D., VAN DER ZEL, D.W. and SKOROZEWSKI, R. (1989). *General Concepts and Approaches to In-stream Flow Assessment*. South African National Scientific Programmes Report 162. CSIR, Pretoria, South Africa.

PALMER, C.G., MULLER, W.J., GORDON, A.K., SCHERMAN, P.-A., DAVIES-COLEMAN, H.D., PAKHOMOVA, L. and DE KOCK, E. (2004). The development of a toxicity data-base using freshwater macroinvertebrates, and its application to South African water resource protection. *South African Journal of Science*, **100**: 643-650.

PARTRIDGE, T.C., DOLLAR, E.S.J., MOOLMAN, J. and DOLLAR, L.H. (2010). The geomorphic provinces of South Africa, Lesotho and Swaziland: A physiographic subdivision for earth and environmental scientists. *Transactions of the Royal Society of South Africa*, **65**(1): 1-47.

ROOS, H. (2004). Genetic diversity in the anabantids *Sandelia capensis* and *S. bainsii*: a phylogeographic and phylogenetic investigation. Unpublished PhD Thesis, University of Pretoria, South Africa. 115 pages.

ROUX, D.J., STIRZAKER, R.J., BREEN, C.M., LEFROY, E.C. and CRESSWELL, H.P. (2010). Framework for participative reflection on the accomplishment of transdisciplinary research programs. *Environmental Science and Policy,* **13**(8): 733-741.

ROWNTREE, K.M. and DU PLESSIS, A.J.E. (2003). *Geomorphological Research for the Conservation and Management of Southern African Rivers: Volume 1: Geomorphological Impacts of River Regulation*. WRC Report No. 849/1/03. Water Research Commission, Pretoria, South Africa.

RUSSEL, I.A. and IMPSON, N.D. (2006). Aquatic systems in and adjacent to Agulhas National Park with particular reference to the fish fauna. *Koedoe,* **49**(2): 45-57.

RUSSEL, B. (1951). *The Impact of Science on Society*. Columbia University Press, New York.

SAGASTI, F. (2004). *Knowledge and Innovation for Development: The Sisyphus Challenge of the 21st Century*. Edward Elgar, Cheltenham, UK.

THORNTON, J.A., BEEKMAN, H., BODDINGTON, G., DICK, R., HARDING, W.R., MORRISON, I.R. and QUICK, A.J.R. (1995). The ecology and management of Zandvlei (Cape Province, South Africa) an enriched shallow African estuary. In: A. McCOMB (Ed.), *Eutrophic Shallow Estuaries*. CRC Press, New York. 109-128.

THORNTON, J.A. and HARDING, W.R. (1998) Phosphorus modelling of African lakes. Report to the Committee for Inland Fisheries of Africa: Fifth Session of the Working Party on Pollution and Fisheries. FAO Fisheries Report 587, Accra, Ghana.

THORNTON, J.A. and HARDING, W.R. (2003). Eutrophication in African Lakes, with Particular Reference to Phosphorus Modelling, in: T.L. CRISMAN, L.J. CHAPMAN, C.A. CHAPMAN and L.S. KAUFMAN (eds), *Conservation, Ecology, and Management of African Fresh Waters*, University Press of Florida, Gainesville, pages 321-341.

TURPIE, J., KLEYNHANS, M. and MALAN, H. (2010). *Wetland Valuation Volume IV – Protocol for the quantification and valuation of wetland ecosystems services*. WRC Report No. TT 443-09. Water Research Commission, Pretoria, South Africa.

VAN HALDEREN, A., HARDING, W.R., WESSELS, J.C., SCHNEIDER, D.J., HEINE, E.W.P., VAN DER MERWE, J. and FOURIE, J.H. (1995). Cyanobacterial (blue-green algal) poisoning of livestock in the western-Cape province of South Africa: 3 case reports. *Journal of the South African Veterinary Association,* **66**(4): 260-264.

WILSON, E.O. (1998). *Consilience – The Unity of Knowledge*. Vintage Books, New York, New York, USA.

WISHART, M.J., DAVIES, B.R., STEWART, B.A. and HUGHES, J.M. (2002). *Examining Catchments as Functional Units for the Conservation of Riverine Biota and Maintenance of Biodiversity*. WRC Report No. 975/1/02. Water Research Commission, Pretoria, South Africa.

WISHART, M., HUGHES, J., STEWART, B.A. and IMPSON, N.D. (2006). Extreme levels of intra-specific divergence among Cape Peninsula populations of the Cape galaxias, *Galaxias zebratus* Castelnau 1861, reveals a possible species complex. *African Journal of Aquatic Sciences*, **31**(1): 99-106.

WOODFORD, D.J. and D. IMPSON, N.D. (2005). Invasive fish in the Fynbos: a major threat to the conservation of a unique floral kingdom. *African Wildlife,* **59**(2): 24-25.