WRC@50

CELEBRATING A HALF-CENTURY OF EXCELLENCE

WATER RESEARCH COMMISSION

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Editors: Jenny Day, Belinda Day, Jody Reizenberg

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PREFACE

Congratulations to the WRC for fifty years of investment in the future of South Africa's waters and the people who care for and manage them! We salute the foresight of those early pioneers in the field who recognised the value of an organisation dedicated to water research and found a sustainable way of making it happen.

Putting this book together has been a challenge and also an eye-opener. When Bonani Madikizela asked us if we would take on the challenge, we were aware that we would need the enthuiastic collaboration of many of our colleagues. But we were unaware of the enormous amount of work that the WRC has funded over the last 50 years, the number of students supported to graduation, and the extent to which this funding has allowed us to grow as scientists and managers of our inland waters. No other country has a similar funding mechanism, and we South Africans can count ourselves fortunate to have the financial and logistical support of the WRC as we go about our research.

The WRC has existed through challenging times in South Africa's history, and not only through the enormous political changes that have resulted in a focus on water provision and sanitation for all South Africans. Management of our freshwater resources has also had to deal with the trade-offs between development and environmental sustainability, conflicts between these two approaches now greater and more critical than they have ever been. Profound changes in the country's water laws have have changed the way that water is viewed – as a common good under the care of the State rather than individuals, and as a necessary component of aquatic ecosystems. Furthermore, increasing co-operation and respect between engineers and ecologists - a phenomenon that was pioneered in South Africa – has led to fruitful collaborations and integration of all aspects of freshwater science and engineering into planning and management of our freshwater resources. And today, other new and wicked challenges - climate change, restoration of impaired rivers and wetlands, and micropollutants – are being tackled by the WRC-funded research community.

"To gear modern knowledge to water resource development and utilisation there must be effective coordination of the research being undertaken by various organisations…In view of the importance and interdisciplinary requirements of water research, the Commission deems it essential that a specific committee for water research be established."

RSA Commission of Enquiry into Water Matters Report, 1970

The book starts with a chapter on the history of the WRC, outlining the reasons for its existence. It ends with a critique of the Commission, touching on controversial issues and suggesting future paths that will build on what has already been done. There have been, and still are, controversies relating to what research should be encouraged and funded, and how to make water science an inclusive enterprise. Overall, though, we can be proud of our achievements and our commitment to a bright future for water in this country.

A very long list of acronyms occurs at the end of the book, together with brief biographical sketches and photographs of the authors.

Asterisks on reference citations

We considered that one of the major benefits of a volume like this would be the collation of many of the thousands of WRC Research Reports and Technical Transfer documents in one easily accessible place. To keep the reference list as short as possible, we have cited in full all the references that are not WRC Reports but for the reports themselves we provide just the authors, the date, the title of the work and the WRC report number. Also, for ease of reading we have not indicated in the text whether a citation refers to a WRC-funded document or not; instead, an asterisk indicates this: for instance, Dlamini and Smith (2034*) will refer to a WRC report.

Jenny Day
Jody Reisenberg
Belinda Day

FOREWORD BY THE WRC CEO

Water is the basis of all life. It is a critical resource, indispensable not only for the maintenance of human life and health but also for the conservation of ecosystems and the socio-economic advancement of any country.

South Africa is a dry country and has been throughout its modern history. Ingenuity, knowledge and innovation have had to be the mainstays of water security from the very beginning. The indigenous inhabitants, the Khoi and San, were successful only because they developed smart ways to store and transport water in our largely semi-arid country where only 10% of the land area constitutes the headwaters for more than 50% of all of South Africa's scarce water resources.

It was during one of the worst droughts ever experienced that the South African government recognised the need for research and development to underline water policy and management in the country. The final report of the Commission of Enquiry into Water Matters, published in 1970, noted: "To gear modern knowledge to water resource development and utilisation there must be effective coordination of the research being undertaken by various organisations…In view of the importance and interdisciplinary requirements of water research, the Commission deems it essential that a specific committee for water research be established." As a direct result, with the promulgation of the Water Research Act (Act no. 34 of 1971) on 1 September of that year, the Water Research Commission (WRC) came into being.

Since then, the WRC has enjoyed 50 successful years of servicing the water knowledge and innovation needs of South Africa, with major contributions to the global environment. The WRC has grown to be South Africa's premier funding agency dedicated to water research. The Commission is considered a 'glue institution' for the South African water research and innovation community of practice. It has also contributed to global institutional development, being a founder member of the International Water Association (IWA) and the Global Water Research Coalition (GWRC). It can claim to be a pioneer in the domain of reverse osmosis as a treatment methodology, piloted dry cooling for electricity generation as a world first, had international recognition for the work it funded on the environmental Reserve and many others.

Today, the WRC's annual budget exceeds R300 million of which two thirds is applied to research and development. The water research levy remains the Commission's main source of revenue. These levies are derived as a percentage placed on bulk water consumption. In essence, the WRC provides and funds applied knowledge and water-related innovation for the improvement of the lives of the citizens who help fund the research to start with. Additional leverage funding is provided by research partners. Research activities are grouped under three main thematic areas, namely water resources and ecosystems, water use, wastewater and sanitation futures, and water utilisation in agriculture.

Every year the WRC funds an average of 100 projects, indicating a significant contribution to knowledge in the water and sanitation sector. The impact of this research, development and innovation can be seen across the sector, from the delivery of quality drinking water and safe sanitation to communities; enhanced water and effluent practices in industry and mining; decision-support for irrigation schemes and for various agricultural sectors; technologies to augment conventional water supply such as fog harvesting, artificial groundwater recharge, wastewater reclamation and desalination; to enhancing fundamental understanding of climate change and improved protection and management of natural resources.

The body of water-centred knowledge created by the WRC and its research partners have been fundamental in the shaping of water legislation in South Africa. At the dawn of democracy in 1994 the WRC was a proud and crucial roleplayer in efforts by the then Department of Water Affairs & Forestry and Minister Kader Asmal to establish the first real legislative framework for comprehensive water management in South Africa.

Many years of cutting-edge WRC research had no place in the water legislation that preceded the National Water Act (Act no. 36 of 1998), but it was sufficiently advanced to be taken up into the new water law principles, the policy and legislation. These included studies in the areas of environmental flows, integrated catchment management, free basic water and small-scale irrigation, among others. The WRC was also able to fund consultancy research projects or initiate direct research projects to assist with various technical aspects and questions that arose during the drafting process.

The impact of the WRC's research is now benchmarked in terms of policy uptake, in terms of broader public dissemination and understanding of trends in water research and development in South Africa and how it compares to international standards and trends. Efforts are made to continuously and carefully define and redefine the role of the WRC in the water knowledge value chain.

The National Water and Sanitation Master Plan, launched by the Department of Water and Sanitation in 2019, has reaffirmed the role of research, development and innovation in developing a robust water sector that can support socio-economic opportunities for the country while managing South Africa's scarce water resources in a sustainable manner.

For many years, particularly in the last ten, the WRC has been a beacon of transformation in the water and sanitation sector. The Commission has achieved important milestones, such as having the majority of project leaders being from the category of black, women and youth. The students supported on WRC projects are predominantly black and majority female. This has been achieved with the generous mentor contributions of senior researchers and innovators. This has also facilitated an important diversification of the research and innovation enterprise, with a higher emphasis on impact and innovation. It represents a model that should be replicated throughout the South African National System of Innovation. Largely thanks to the WRC's capacity building efforts, today, the South African water science sector, albeit small in size, is considered highly productive and is rated highly internationally.

It is perhaps fitting that the WRC is celebrating its fiftieth year of existence amid one of the worst pandemics the world has ever witnessed. The worldwide outbreak of COVID-19 has not only disrupted the social and economic realities of our communities, but also underscored the importance of water to health, hygiene and safety. While lockdown restrictions disrupted research work some WRC funding was redirected towards fighting the pandemic. This included the provision of laboratory and research work services on the monitoring of SARS-CoV-2 in wastewater and faecal sludge as a means of estimating the prevalence and burden of COVID-19 infections in communities. This has not only provided fundamental support to the South African Government in the fight against the pandemic, but has placed the local science community on the global platform.

Through five decades of activities the WRC has firmly entrenched itself in the water and sanitation sector in South Africa. It remains dedicated to the creation of a water secure society for all of South Africa's citizens.

Dhesigen Naidoo
WRC Chief Executive Officer

ACKNOWLEDGEMENTS

It was a great pleasure to work with several WRC personnel in the preparation and production of this book. The timeline for the project was tight, so their efficiency and professionalism are greatly appreciated. Bonani Madikizela steered the project from inception to completion, efficiently assisted by the unflappable Gerda Kruger. Lani van Vuuren and Anja van der Merwe were responsible for production of the final copy, Lani as production editor while Anja as graphic designer and layout artist. We are really proud of the look of the book, as well as its contents.

The authors deserve special thanks. Almost everyone who was approached to write a section of the book agreed to do so without hesitation, and produced some fascinating insights into their disciplines, mostly on time and mostly without complaint when reviewers asked for modifications and additions to their sections. A few "orphaned" sections had to be written in something of a rush and we are particularly grateful to their authors for assisting quickly and willingly.

I never cease to be amazed by the commitment, enthusiasm and efficiency of our post-graduate students. Some (Melandri Steenkamp, Faeeza Fortune, Lerato Phali, and Mohammed Kajee) are co-authors of chapters. Errol Malijani (Water Services) and James Machingura (Ecosystems) took on the unenviable job of coordinating two of the largest and most unwieldy chapters. They managed "their" authors with aplomb, even though they were the junior partners in the team. Other students (Yonela Mkunyana and Eugene Maswanganye) very efficiently extracted reports from the unwieldy and unfriendly WRC website and delivered them to the authors with very short turnaround times. This was a really important part of the process and we are particularly grateful to all of them. With students like this, we do have hope for the future of water science and management in this country.

It is always reassuring to have thorough reviews of books like this one that are not subject to the normal formal peer-review process. In our case, every chapter was reviewed by a senior scientist in the relevant discipline. Again, timelines were short but reviewers produced their reports and recommendations quickly and efficiently. We thank George Green, Andre Görgens, Hans Beekman, Mike Shand, Nabojsa Jovanovic, Heather Malan, Tony Turton, Bruce Paxton, Darragh Woodford, Dean Ollis, Alan Whitfield, Sharon Pollard, and James Cullis for chapter reviews. We also thank Charles Breen and Mike Silberbauer for reviewing the entire volume. We are happy to say that the reviews have generally been very positive, which gives us confidence that we have produced an excellent book. Thank you, everyone

Jenny Day
Jody Reizenberg
Belinda Day

August 2021

INTRODUCTION

STEVE MITCHELL

The mid-1960s was a time of very bad drought, in some areas the worst for a century. This led to the report of the Commission of Enquiry into Water Matters, appointed in 1966, being accepted as Government Policy in 1970. It was apparent that if the then current manner in which the country's water resources were being managed were to continue, it would only be a matter of time before water shortages and poor-quality water would increasingly limit economic growth. There was a need to relook at water resource management with a view to improving its efficiency.

The then Minister of Water Affairs, Hon. Fanie Botha, saw that it was of national importance for a statutory body be established to promote and expedite the country's water research purposefully. The Water Research Act (Act 34 of 1971) was passed by Parliament and the Water Research Commission (WRC) was established (Water Wheel, 2011). Dr JP Kriel, then Secretary of Water Affairs, was the ex officio chair of the newly-formed WRC and Dr Gerrie Stander was the Chief Executive Officer.

The mandate (see text box) has remained fundamentally unchanged through the five decades of the life of the WRC.

The mandate of the newly established WRC was:

- **to promote, coordinate, cooperate and communicate in the area of water research and development;**
- **to establish water research needs and priorities;**
- **to stimulate and fund water research according to priority;**
- **to promote effective transfer of information and technology;**
- **to enhance knowledge and capacity building within the water sector.**

Water Wheel 2011

Following Dr Stander's retirement in 1979, Dr Matt Henzen was appointed CEO. Dr Henzen retired in 1985 and was followed by Mr Piet Odendaal who was the Executive Director until his retirement in 2000. Dr George Green acted as Executive Director until Dr Rivka Kfir was appointed as CEO in 2001, a position she held until 2011. She was followed by Mr Dhesigen Naidoo.

By the end of the first decade of the WRC's existence, the staff complement reflected a strong bias toward engineering aspects of water research. After this period the scope was broadened with the recognition of the importance of the biophysical, ecological, economic and social aspects and the appointment of new staff members reflected this broadening interest.

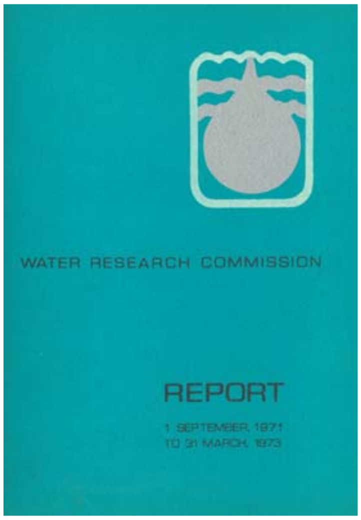


Figure 1: The first Annual Report published by the WRC in 1973.

One early and very significant policy decision was that the WRC would be separate from the Department of Water Affairs. This decision was taken to allow the WRC to identify future needs and trends in the country's development and to be ready with water management options as the need arose. To this end, funding needed to be independent of the government fiscus. The model that was implemented was to levy a small charge on water use by bulk suppliers such as the water and irrigation boards. This ensured that research funding would be consistent and not subject to budget cuts by Treasury. This model was designed to allow research organisations to build their work on a predictable funding base and to provide appropriate science for management rather than to follow the political trends of the time. This predictability has been a boon both to organisations carrying out the research and to the building of research capacity in the country which, in turn, has enabled the country to develop its capacity to manage the resource.

Another early policy decision was that the WRC staff would not conduct research themselves but would contract the research to institutions, such as universities. This gave the WRC the agility to quickly take on new research thrusts as the need was identified without having to re-skill staff.

Some time after the mid-1980s, the heads of eminent water research institutions (focusing mainly on water and wastewater treatment) from different countries came together and instituted a voluntary rotational peer-review system, whereby one of the member organisations would periodically be reviewed by the heads of the remaining members (Mr Piet Odendaal in the case of the WRC). The WRC was unique among members, as it was the only one to exclusively manage research through funding, with no mandate to perform research of its own. Member organisations were (one each) from South Africa, the USA, UK, several European countries and Australia. Implementation of review panel recommendations served to promote a high level of corporate and research management among members.

RESEARCH IDENTIFICATION AND MANAGEMENT

The system of project management adopted from the beginning of operations was that each project had a steering committee which met annually unless there was a need for more frequent discussions. Steering committees generally included researchers who were involved in the research field, officials from relevant government departments, and practitioners who were in a position to advise on the application of the research products. In this way, while the standard of the research was maintained at a high level, the research products were kept relevant to the identified needs being addressed.

The WRC is unique in that it funds research across the entire water cycle. This has permitted it, over the decades, to fund research into the development of new areas as the need has been seen to arise (see Figures 2, 3 and 5). Initially, research was largely focused on engineering issues. An early success was the direct recycling of treated municipal wastewater in Windhoek, which was a world first.

Another early success was the long-running project on rainfall stimulation using cloud seeding technology. This was first identified as an avenue for research in 1973 when the development and application of techniques for the stimulation of rainfall was put forward. The first project on this, based in Bethlehem in the Eastern Free State, was funded in 1975. This research was co-funded with the Weather Bureau of the Department of Environmental Affairs. A second cloud seeding node was opened in the Lowveld at Nelspruit in 1978. The research field of rainfall stimulation eventually merged with the field of hydroclimatology. This project was well funded and, at its peak, received more than 25% of the funding allocated to research. Figure 2 shows funding allocated to this research as a percentage of the total funding allocated to research. At its peak in 1983 it received 36.67% of the funding allocated to research.

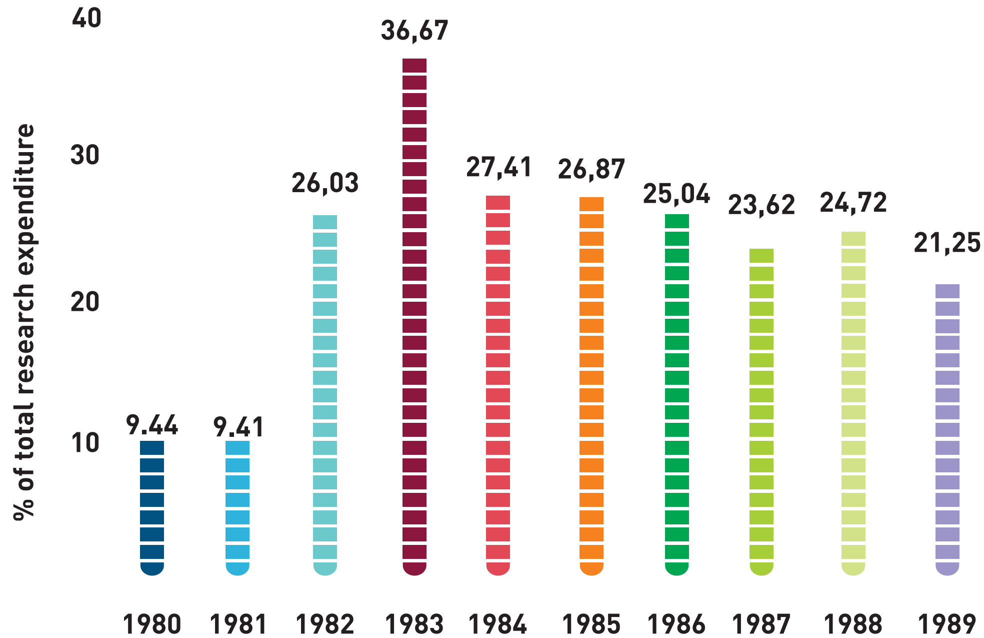


Figure 2. Funding of research on rainfall stimulation expressed as a percentage of total WRC research expenditure (1980 to 1989).

The success of the cloud seeding programme is illustrated in Figure 3.

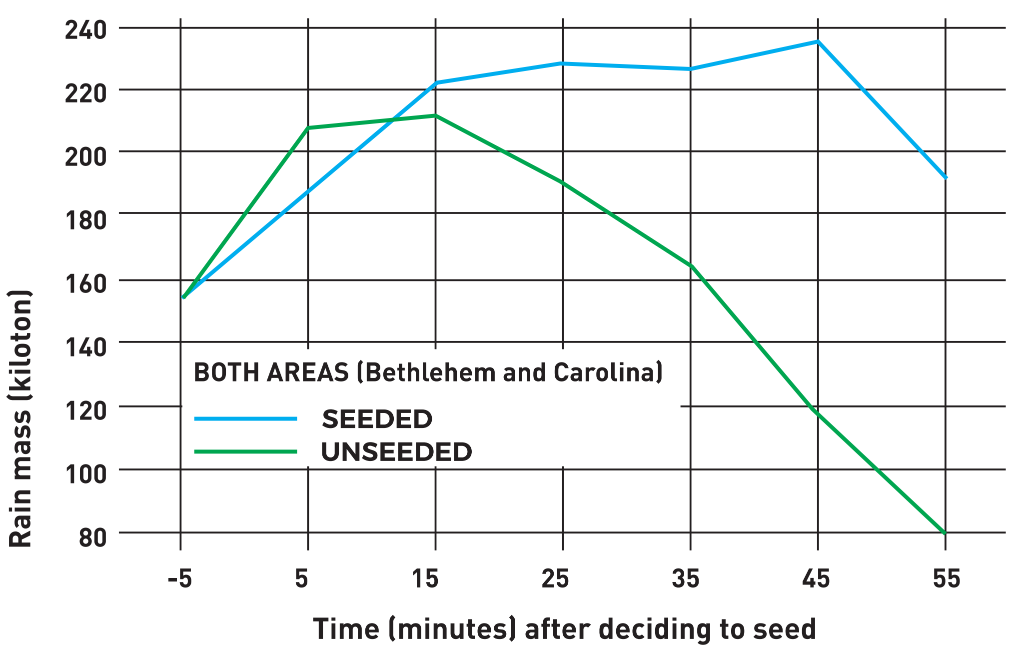


Figure 3. Showing the improvement in precipitation of seeded over unseeded clouds.

This programme showed that, under the correct circumstances, rainfall stimulation is an option for increasing precipitation.

Amongst the other successes from this period was the biological removal of phosphate from sewage effluent. Previously, phosphate had been removed through chemical precipitation, but this process increased the salinity of effluents, which would thereafter be discharged into a water resource, usually a river. Discharge of salinised effluents is undesirable in a water-scarce country, so the biological removal of phosphate was an important step in managing the water quality of receiving rivers. Another example of WRC research that has been employed internationally is the STASOFT computer program. This program was developed to guide the softening and stabilisation of municipal water during the 1980s.

The modus operandi of the WRC remained fundamentally unchanged until Dr Kfir took over the reins in 2001. She introduced a number of changes, many of which are still maintained, but possibly the most influential development was arranging topics in Key Strategic Areas (KSAs), introducing a level of stability to the categorisation of research fields.

But it was 'the Red Book', published by the Department of Water Affairs in 1986 (DWA, 1986) that opened the funding field to other issues, notably social and environmental issues, in the management of water resources. From this time the WRC started funding research into topics addressing policy, social, institutional and natural environmental topics. Initially, the environment was categorised as a competing water user, but this view gradually changed and now the environment is considered to be part of the resource and a 'requirer', rather than 'consumer', of water. Up to this time steering committee membership had largely been male, but now the membership expanded to include women as well. This exposed an unforeseen problem in the services provided by the WRC. Meetings were held on the top floor of the building and ablution facilities were provided here for steering committee members, and these catered only for men. Women had to go to the floor below at the other end of the building where the ladies' facilities were situated to accommodate the needs of the secretaries! The situation was eventually remedied.

Among the research initiatives started at this time was the quantification of the water needed to be kept in the natural environment in order to maintain environmental functioning. Methods were available to address specific aspects of streamflow, but the Building Block Methodology (BBM) was the first holistic method to address the suite of needs of the riverine ecology. Following the BBM, the DRIFT (Downstream Response to Imposed Flow Transformations) method was developed, and this has been widely used internationally (see Chapters 2 and 10 for details and references).

IDENTIFICATION OF RESEARCH NEEDS

Coordinating Research and Development committees commenced in 1976 as a strategy to identify national research needs. There was a committee for each of the main research areas. These committees were composed mainly of researchers involved in the specific field as well as officials from government departments or other implementing agencies. Sometimes end-users were included not only to assist in needs identification, but also to build their capacity in applying emerging knowledge and technology. The task of these committees was to identify future research trends and to give guidance to the WRC on the initiation of emerging research thrusts that needed to be developed.

RESEARCH FIELDS TIMELINE

The information discussed below is available in the Annual Reports and, more recently, the Knowledge Reviews of the WRC. There was a change in the management of the research fields between 2000 and 2001. Up to 2000, new initiatives were opened as the need arose, and from time to time some of the names of the fields were changed to take account of shifts in the emphasis of the field with the development of new knowledge (Figure 5). From 2001 onwards, the categorisation of the research fields was changed to KSAs.

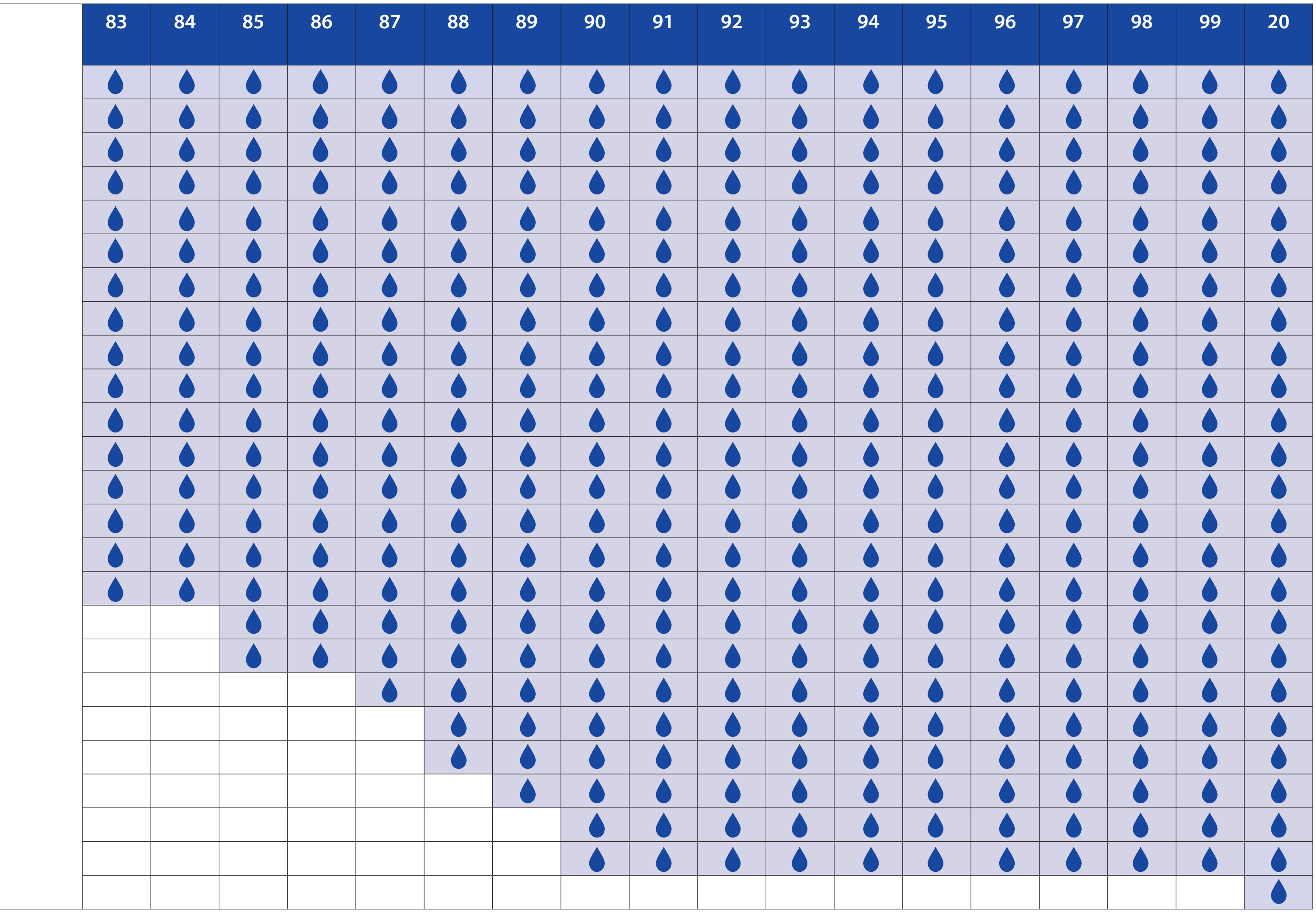
Figure 5 shows the timeline of the research undertaken between 1972 and 2000. The fields are arranged in the order in which they were initiated. The descriptions of the research fields are self-explanatory.

Figure 4. From the 2000s onwards, the environment became an important research topic for WRC-funded projects.

Research field	72	73	74	75	76	77	78	79	80	81	82
Urban water supply											
Municipal effluent (incl. sludge handling)											
Industrial effluents											
Water economy at power stations (e.g. dry cooling)											
Eutrophication											
Surface hydrology											
Water treatment and reuse											
Potable water – health aspects											
Integrated urban water management											
Groundwater											
Hydrometeorology											
Rainfall stimulation											
Agricultural water utilisation											
Flood damage											
Membrane technology											
Water reclamation											
Marine disposal of effluents											
Water restrictions – socio-economic											
Policy											
Developing communities											
Rural and urban water supply											
Conservation of ecosystems											
Geological aspects											
Institutional aspects											
Integrated water resource management											

Figure 5: The fields in which WRC-funded research was active between 1972 and 2000 are shown in mauve.

After 2000, research continued within the KSA structures. The research needs of the natural infrastructure were addressed by KSA 1 (Water Resource Management) and KSA 2 (Water-linked Ecosystems). The research needs of the built infrastructure were addressed through KSA 3 (Water Use and Waste Management) and KSA 4 (Water Utilisation in Agriculture). Each KSA was divided into thrusts, and each thrust was divided in programmes. The projects funded were categorised within the programmes. Figures 6 and 7 show the KSAs and their associated thrusts. In each figure, the thrusts highlighted in light blue indicate those which were either discontinued or restructured to include new research areas.



"'The Red Book', published by the Department of Water Affairs in 1986 (DWA, 1986) that opened the funding field to other issues, notably social and environmental issues, in the management of water resources"

KSA 1	Water resource management	Thrust 1	Water resource assessment
		Thrust 2	Integrated water resource development
		Thrust 3	Management of natural and human-induced impacts on water resources
		Thrust 2	Water quality management
		Thrust 3	Water resource protection
		Thrust 4	Policy development and institutional arrangements for water resource management
		Thrust 4	Water resource institutional arrangements
		Thrust 5	Water resources and climate
KSA 2	Water-linked ecosystems	Thrust 1	Ecosystem processes
		Thrust 2	Ecosystem management and utilisation
		Thrust 3	Ecosystem rehabilitation, remediation, and restoration
		Thrust 4	Sustainable ecosystem utilisation and development
		Thrust 5	Ecosystems and global change

Figure 6. The research thrusts within KSAs 1 and 2, showing when they were active.

KSA 3	Water use and waste management	Thrust 1	Water services: Institutional and management issues
		Thrust 2	Water supply and treatment technology
		Thrust 3	Wastewater and effluent treatment and reuse technology
		Thrust 3	Sustainable municipal wastewater and sanitation
		Thrust 4	Industrial and mine-water management
		Thrust 4	Sustainable and integrated industrial water management
		Thrust 5	Sanitation and hygiene education
		Thrust 5	Mine-water treatment and management
		Thrust 6	Water Smart Fund

	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18

	2002/03	2003/04	2004/05	2005/06	2006/07	2007/08	2008/09	2009/10	2010/11	2011/12	2012/13	2013/14	2014/15	2015/16	2016/17	2017/18

KSA 4	Water utilisation in agriculture	Thrust 1	Water utilisation for food and fibre production
		Thrust 1	Water utilisation for food, forage and fibre production
		Thrust 2	Water utilisation for fuelwood and timber production
		Thrust 3	Water utilisation for poverty reduction and wealth creation in agriculture
		Thrust 4	Water resource protection and reclamation in agriculture

Figure 7: The research thrusts within KSAs 3 and 4, showing when they were active.

In addition to the KSAs, cross-cutting domains were introduced. These provided specific mechanisms for addressing issues of national importance. The research projects themselves were managed from within the relevant KSA but the cross-cutting domains ensured that interests that were wider than those addressed within individual KSAs were considered.

The initiative to solicit specific research was introduced with the transformation of the WRC during 2001/02. Such needs were identified during stakeholder communications or other, sometimes international, consultations. A call for solicited projects included the aspects to be addressed by the project, and a proposed budget. Figure 8 shows the number of solicited projects against the total number funded.

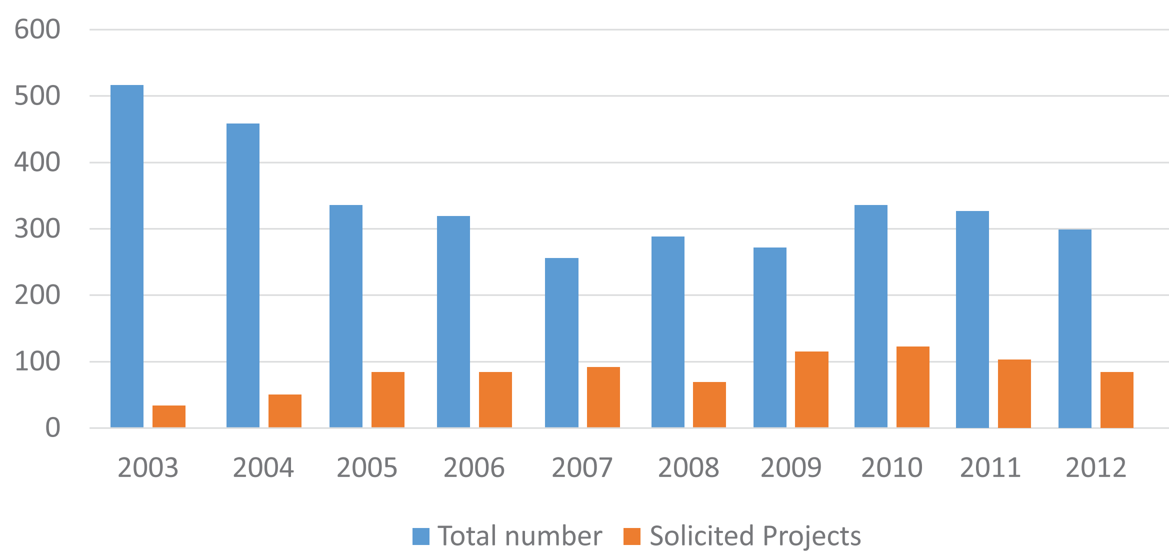


Figure 8: Number of projects (Total and Solicited) funded between 2003 and 2012.

Two trends in project funding are evident from Figure 8. The first is that the total number of projects decreased. This is the result of the average project budget increasing. The second is that the proportion of solicited to total number of projects increased during the decade for which data are available in the Annual Reports.

Two important initiatives to support the WRC research were started in 1975. These were the publication of ***Water SA*** and the ***SA Waterbulletin***. Both of these are ongoing. ***Water SA*** publishes original research and review articles on all aspects of water science. The first edition was published in April 1975 and the journal has been published quarterly since then. ***Water SA*** is the top-rated African water journal, publishing papers from throughout the continent. It has a very respectable Impact Factor of 1.206 (2019) and is one of the most important research-related products of the WRC. The ***SA Waterbulletin*** is a magazine contributing to water consciousness at all levels of South African society. It contains articles, news items and items of general interest on many aspects of water in South Africa and internationally. The ***SA Waterbulletin*** was first published in August 1975. During 2002, the name was changed to ***the Water Wheel***, with greater emphasis being placed on visual representation and highlighting the human element, wherever possible. It has been published bi-monthly since its inception.

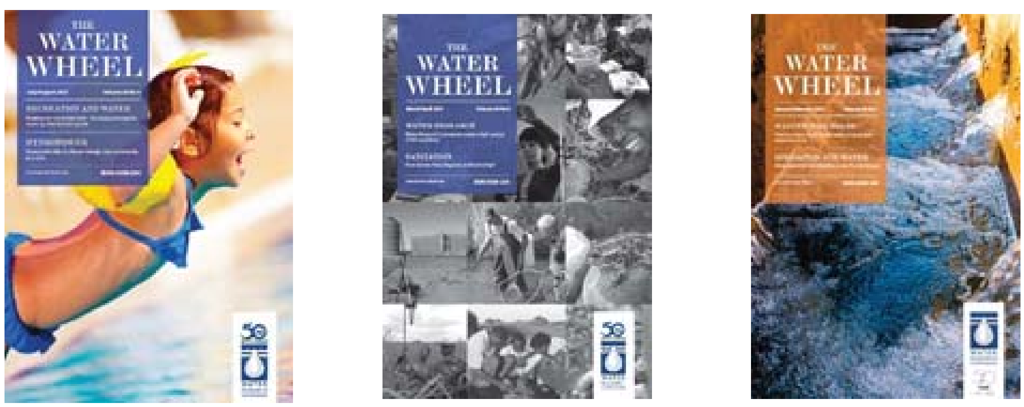


Figure 9. The SA Waterbulletin was renamed the Water Wheel in 2002.

FUNDING – LEVY AND LEVERAGE

As stated above, the WRC was initially funded through a small levy on water sold by the state to the government water and irrigation boards. This gave the WRC the capacity to undertake a substantial amount of research. In some cases, supplementary funding was obtained from the end-users of the research, giving the end-user a stake in the direction of the research. Importantly it also gave the end-user the time to prepare to implement the research findings as well as the insight into what would be required for its implementation.

Dr Kfir introduced the concept of leverage funding early on during her term of office. This involved managing funds from sources other than the WRC, expanding the reach of the research conducted by the WRC, giving the WRC-funded work wider exposure than would otherwise be possible and enhancing knowledge dissemination. The leverage was realised in a number of ways apart from the supplementation of funding. It could include 'in kind' assistance such as the provision of equipment or personnel for specific projects. The Annual Reports from 2004/05 to 2011/12 give the total of funds obtained from other sources as a percentage of the total funds for the organisation (Figure 10). In addition, these reports give the percentage of funds from leverage as a percentage of the funds obtained from other sources. From this, the percentage of the total funds obtained by leverage has been calculated.

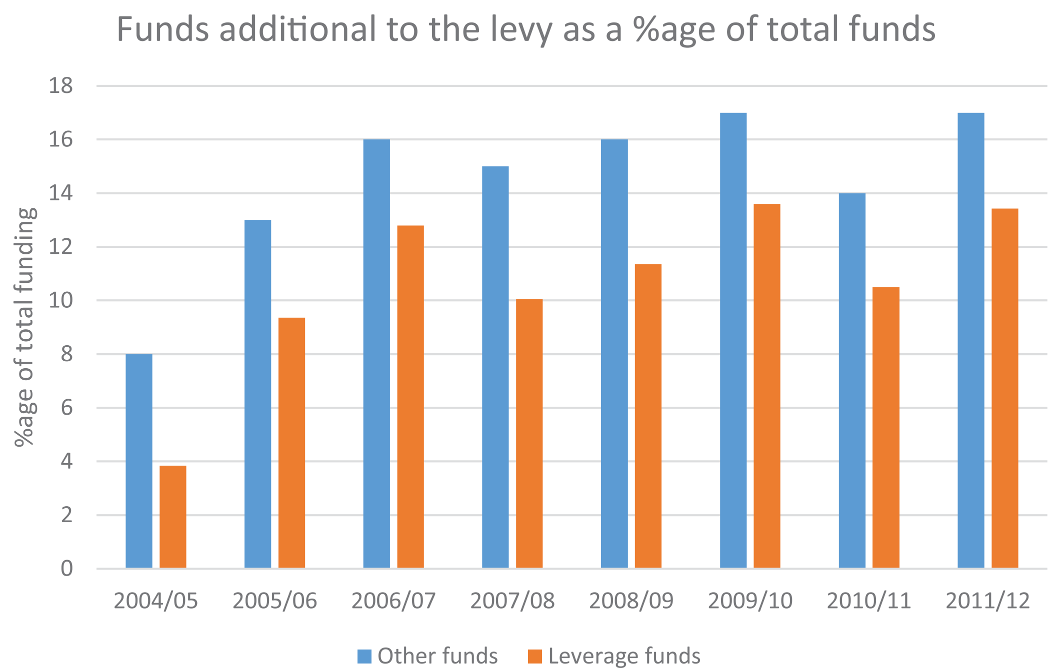


Figure 10: Percentage of non-levy funds obtained during the years 2004/05 to 2011/12.

NOTE: the leverage funding shown in Figure 10 forms part of the percentage of other funding. It is not in addition to the other funding.

CAPACITY BUILDING

An important activity of the WRC has always been the building of research capacity in the country. Prior to 1994 postgraduate students were commonly employed on projects, but building capacity in water research became a priority after the advent of democracy in 1994. The first move was to set funding aside to initiate projects in the old 'homeland' areas and to personnel from these homeland universities to submit research proposals. This resulted in the funding of projects at several of these universities, with some students employed on these projects subsequently making careers in water research and management. Now, some quarter of a century later, several are in leadership positions in water research and the broader water industry.

It was not until 2002, however, that the WRC started recording the number of postgraduate students involved in projects (Figure 11). This figure needs to be read with the understanding that research for an MSc degree normally takes 2 years and for a PhD degree, 3 years.

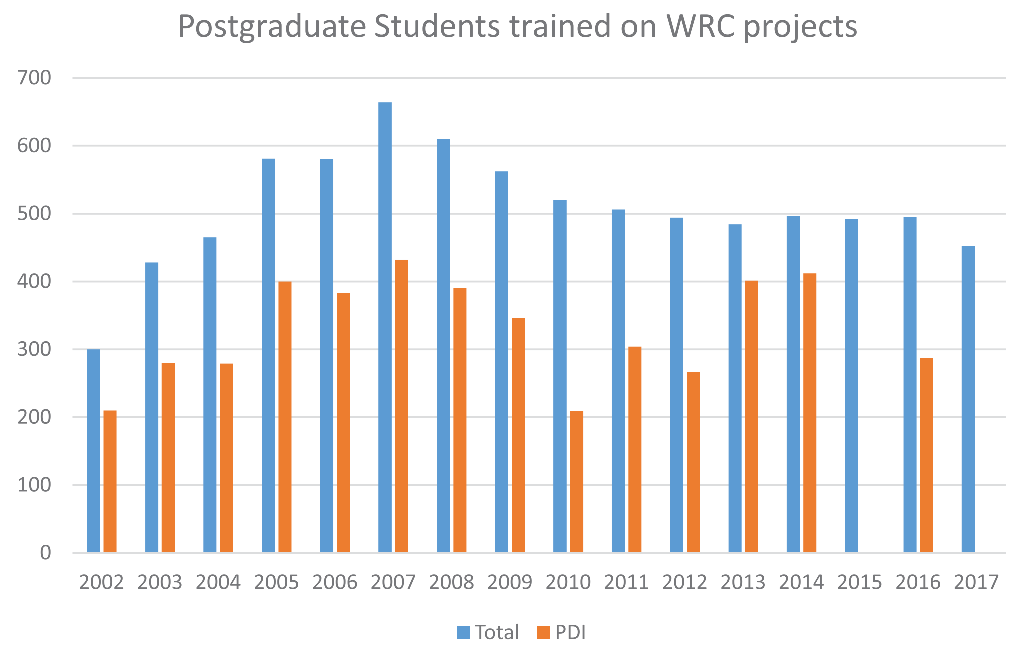


Figure 11: Numbers of postgraduate students in training on WRC projects between 2002 and 2017.

These numbers are taken from the Annual Reports and Knowledge Reviews published from 2002 onwards. The numbers of students from previously disadvantaged backgrounds are not available for 2015 and 2017.

Figure 11 shows that more than 50% of the students involved in WRC projects were from previously disadvantaged backgrounds.

Figure 12. Through the WRC's various capacity building initiatives thousands of postgraduate students have been supported in the sector through the years (Source: Water Wheel archives).

There have also been a number of other capacity-building initiatives. Throughout the existence of the WRC, the Commission has supported consultancy visits to South Africa by international scientists and water technologists. The Commission has also supported, and in some cases assisted in funding, local and SADC-wide capacity building initiatives financed by donors. An example is FETWATER (Framework for the Education and Training in Water), initially co-funded by the WRC and the Belgian government, which started in 1996 and is still running. Another, now terminated, is WARFSA (Water Research Fund for Southern Africa), funded by Sweden.
The WRC has developed a number of guidelines and undertaken a number of case studies for development of capacity in areas in which it has funded research, in keeping with its mandate to promote effective transfer of information and technology and to enhance

knowledge and capacity building within the water sector. For example, the WIN-SA (Water Information Network – South Africa) was a long-running initiative (12 years, from 2005 to 2016) which produced a number of resources. The full list of resources is available at http://www.wrc.org.za/win-sa/.

RECENT DEVELOPMENTS IN THE MANAGEMENT AND DISSEMINATION OF RESEARCH

The WRC has recently introduced two new ways of managing knowledge for dissemination, the Knowledge Tree and the WRC Lighthouses. The Knowledge tree is a fundamental guiding framework and corporate planning tool used by the WRC to define, measure and evaluate research impact. The knowledge tree uses the multiplier effect to inform policy and decision-making, contribute to sustainable development solutions, develop products and services for the economy, actively contribute to human capital development. The six focus areas of the Knowledge Tree are to:

- Inform policy and decision-making
- Develop new products and services for economic development
- Enhance human capital development (HCD) in the water and science sectors
- Drive sustainable development solutions
- Promote transformation and redress
- Empower communities

The Lighthouses are a concentration of research for accelerated knowledge and solution development. These are trans-disciplinary, multi-branch and inter-institutional mega-projects (platforms) that will examine priority water issues across the innovation value chain.

CONCLUSION

In conclusion, the Water Research Commission has, over the five decades of its existence contributed significantly to the national capacity to manage its scarce water resource. The surface water flow of the entire country is a little under 50% of that of the Zambesi, the nearest large river (DWAF, 2004). At the same time, South Africa has the third largest GDP in Africa after Nigeria and Egypt (Figure 13).

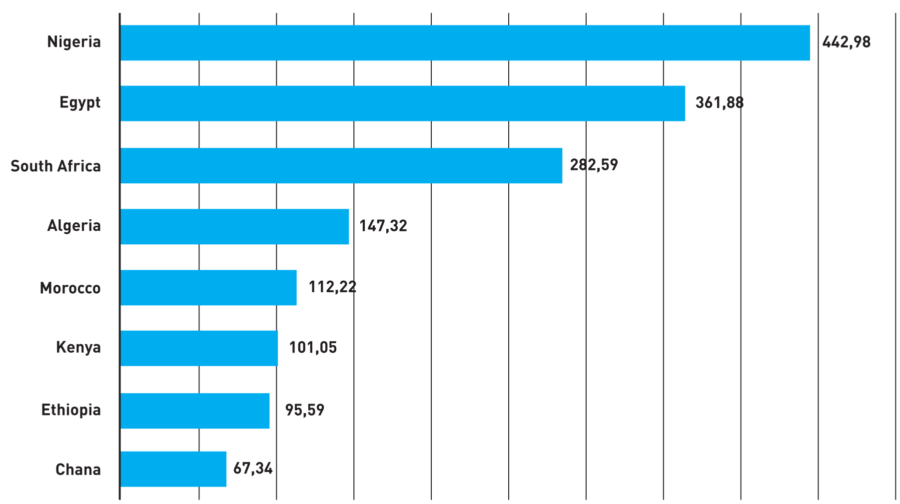
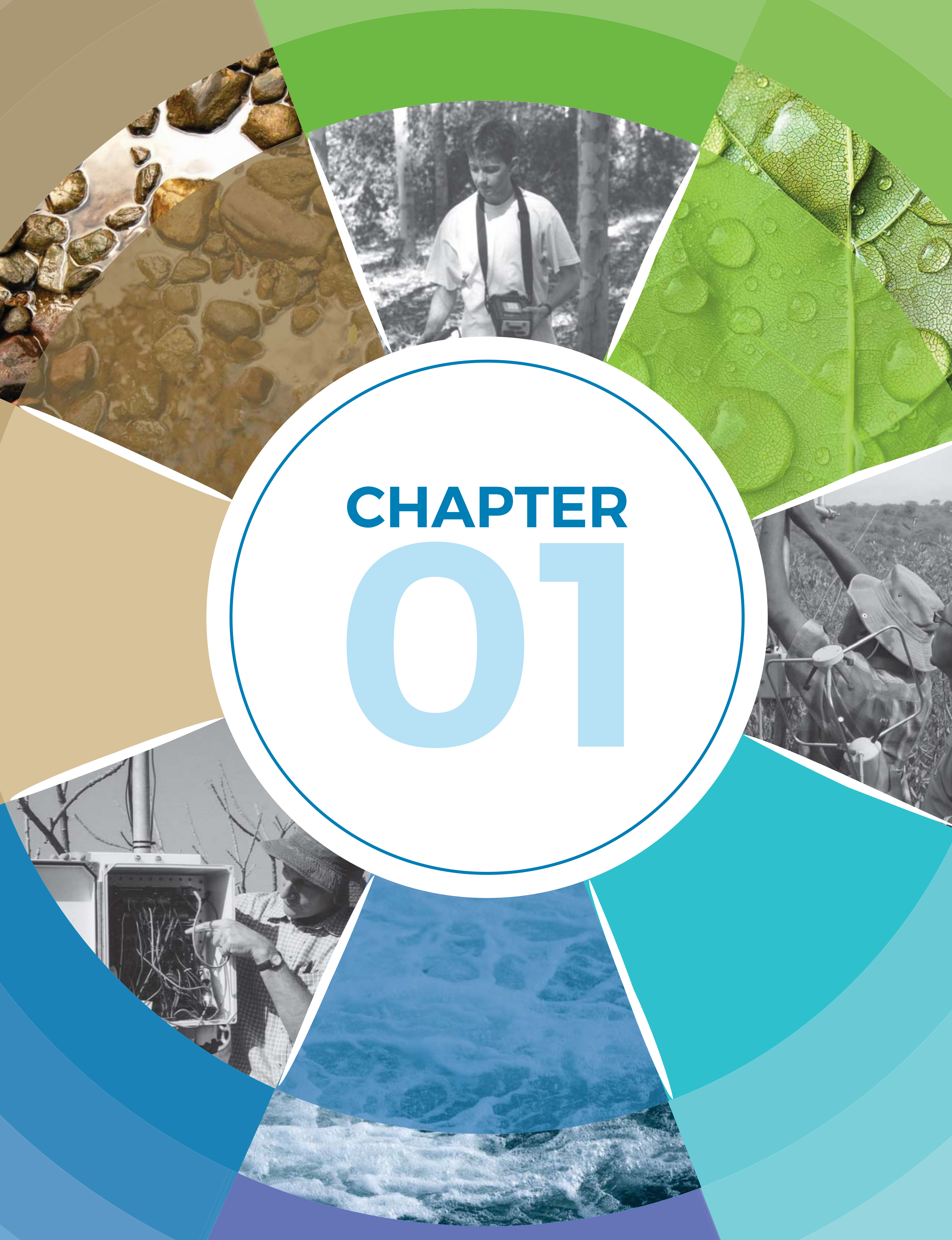


Figure 13: GDP of 8 African countries in 2020 (in billion U.S. dollars)[1]. (Statista.com)

Support of a GDP of this size needs a reliable and adequate supply of water of adequate quality. Research funded and managed by the WRC has done much to bring this about. The following chapters expand on the work done by the WRC and its funded researchers, highlighting some of the groundbreaking South African research that would not have been possible in the absence of the Commission.

[1]https://www.statista.com/statistics/1120999/gdp-of-african-countries-by-country/



CHAPTER 01

HYDROLOGY AND THE WATER RESEARCH COMMISSION IN SOUTH AFRICA

Graham Jewitt

INTRODUCTION

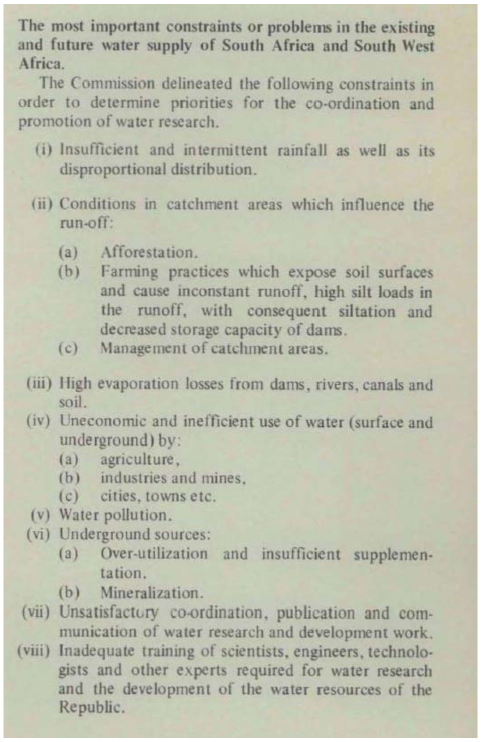
Hydrology, the science that considers the definition and quantification of the processes involved in the movement of water through the hydrological cycle has been strongly supported by the Water Research Commission (WRC) throughout its existence. Internationally, hydrology has evolved into a mature, critical field of enquiry which finds its application in water resources management. Over the years, South African hydrology has established conceptual, empirical, and theoretical foundations evolving as a strong science with international (International Association of Hydrological Sciences; IAHS; https://Iahs.info) and local (the South African National Committee of the International Association of Hydrological Scientists; SANCIAHS) professional societies, as well as strong degree education programmes and a closely related field of practice for professional registration in South Africa (i.e., Pr.Sci.Nat. – Water Resources). Nevertheless, a science that deals with the hydrological cycle in its entirety has difficulty defining its boundaries. Much hydrological research overlaps with areas of water resources planning, agricultural water management, meteorology, and, especially over the past 20 years, with integrated water resources management (IWRM) and policy development.

At the time of the WRC's inception in 1971, hydrological research in South Africa was already well established. Investigations in the well-known Jonkershoek and Cathedral Peak research catchments had been ongoing for several decades and there had been many influential reports produced by local scientists from state departments, research institutes, and universities active in those catchments and their associated research programmes. This work had already had a major role in developing aspects of South Africa's water resources management policies, particularly those associated with commercial afforestation and water-resources planning (see Bennet and Kruger (2013) for a comprehensive analysis). Prof Des Midgley, who is considered South Africa's "father of hydrological modelling" and the Hydrological Research Unit (HRU) at the University of the Witwatersrand which he led, were well known locally and internationally.

Strongly influenced by the 1970 Commission of Inquiry into Water Matters, at its inception, the WRC focused its research strategy on the interaction between two cycles i.e., the hydrological cycle and the water utilisation cycle. In essence, the focus of the commission's work considered that ***"the key to the prevention of restriction of constraints in the Republic's water economy insofar as it is related to social economic development, lies in a synchronised interaction between the water utilisation and hydrological cycles, and that all problems with the water economy related to the interaction of the main components of those cycles" (WRC Annual Report 1973*).***

Using this approach as a guideline, the Commission identified what they believed were the most important constraints to the existing and future water supply in South Africa (and South-West Africa) (Figure 1), with a focus on what were referred to as the "main task areas". Research on the hydrological cycle was a key theme.

*WRC reports have been marked in the text with **



The most important constraints or problems in the existing and future water supply of South Africa and South West Africa.

The Commission delineated the following constraints in order to determine priorities for the co-ordination and promotion of water research.

(i) Insufficient and intermittent rainfall as well as its disproportional distribution.

(ii) Conditions in catchment areas which influence the run-off:

(a) Afforestation.
(b) Farming practices which expose soil surfaces and cause inconstant runoff, high silt loads in the runoff, with consequent siltation and decreased storage capacity of dams.
(c) Management of catchment areas.

(iii) High evaporation losses from dams, rivers, canals and soil.
(iv) Uneconomic and inefficient use of water (surface and underground) by:
(a) agriculture,
(b) industries and mines,
(c) cities, towns etc.
(v) Water pollution.
(vi) Underground sources:
(a) Over-utilization and insufficient supplementation.
(b) Mineralization.
(vii) Unsatisfactory co-ordination, publication and communication of water research and development work.
(viii) Inadequate training of scientists, engineers, technologists and other experts required for water research and the development of the water resources of the Republic.

Figure 1. Most important constraints to the existing and future water supply in South Africa (from the Water Research Commission Annual Report 1971–1973).

Within this rather broad theme, priority areas were identified. By 1973, these had crystallised and a National Master Research Plan and National Priority Research Programme had been formulated. Within the Hydrological Cycle Research theme, the focus areas were:

- insufficient and intermittent rainfall as well as its disproportionate distribution, with a particular focus on the utilisation of atmospheric moisture
- conditions in catchment areas which influence the runoff/river flow
  - afforestation
  - farming practices which expose soil surfaces and cause runoff with high silt loads
  - management of catchment areas
- high evaporative losses from dams, rivers, canals, and soil

This review focuses on water-quantity related research. Apart from the focused research topics, other aspects, such as poor coordination, publication, and communication of water research development work and inadequate training of scientists, engineers, technologists, and other experts, were identified as priority areas. Furthermore, a particular focus on data and information from monitoring resulted in a proposal to develop what was termed a 'National Water Information Centre'

Through the 1980s and 1990s, hydrology enjoyed a strong profile in the WRC. The themes identified in the 1970s continued, with some expansion into hydrological process studies and a widening influence into application into the different aspects of water-resources management. With the restructuring of the WRC after 1998, hydrology was no longer a separate focus area, but became incorporated into the Key Strategic Area (KSA) known as 'Water Resources Management'. To some extent this diluted efforts to elucidate the components of the hydrological cycle and the interactions between them, but did facilitate the more focused application of the science into studies that could be applied – most notably the effects of the management of land use and land cover on water resources, studies to support the implementation of the Ecological Reserve, and the regular series of assessments of the status of the country's water resources. In parallel, the impacts of climate change became a significant aspect of hydrological studies (see Chapter 12 for details).

The themes shown in Figure 1 are too numerous to mention individually. Rather, the approach taken in this chapter is to follow the components of the hydrological cycle where research has been focused and to provide a narrative describing the key research areas and the ways in which the focus has shifted over the past 50 years (Table 1).

Table 1. A hydrological perspective on the research focuses of the Water Research Commission (WRC) from the 1970s to 2020.

1970s	• National Precipitation Research Programme • Small-catchment studies – land use and land cover • Numerical model development – Pitman Model
1980s	• National Precipitation Research Programme continues • Rainfall surfaces for modelling • Small-catchment studies – flood and drought focus • Numerical model development – ACRU Model • First National Water Resources Assessment study i.e., WR81
1990s	• National Precipitation Research Programme ends • Radar rainfall estimates • Daily rainfall database and agrohydrological atlas • Greater focus on hydrology process studies • Improvement of tools for the allocation of water for commercial afforestation • Hydrological analysis to support environmental flow assessments • Climate change research increases • National Water Resources Assessments i.e., WR90
2000 – The new National Water Act	• Shift to 'implementation' and 'hydrology' as components of other initiatives • Hydrology incorporated into Water Resources Management Key Strategic Area • Growing international collaboration in Africa and globally • Climate change studies • Hillslope hydrology, surface-water-groundwater interactions, and low flows • National Water Resources Assessment, i.e., WR2005 • Studies on environmental flows (water allocations for rivers) • Remote-sensing studies emerge
2010	• Co-funding and international funding models • WRC funding on hydrology to support the National Water Act and IWRM • Ongoing focus on large-scale land use and land cover change, including the impacts of invasive alien plant species • Water use of biofuel and other agricultural crops • Hydropedology and related soil initiatives • National Water Resources Assessment, i.e., WR2012

***ACRU** - Agricultural Catchments Research Unit*

***WR (1981)** - Water Resources (year of publication)*

***WRC** - Water Research Commission*

***IWRM** - Integrated water resource management*

Atmospheric moisture (Climate studies/Hydroclimatology)

"Only a small percentage of atmospheric moisture above the land appears to precipitate as rain and supplement water resources. Extraction of moisture from the air, whether by direct means or stimulation of rain, would therefore seem an attractive proposition"
WRC Annual report (1980)*

Hydrometeorological studies focus on understanding, predicting, and exploring whether the manipulation of the important role played by the atmosphere in the hydrological cycle is possible. In the 1970s and 1980s a focus (some would argue a 'fixation') on increasing the utilisation of atmospheric moisture evolved into a large and costly research programme known as the National Precipitation Research Programme. Over time, other hydrometeorological projects developed, but none has seen the prominence that the National Precipitation Research Programme had until the mid-1990s.

The National Precipitation Research Programme (NPRP)

"In view of an expected serious shortage of water soon after the turn of the century, the Commission considers it essential to investigate, in cooperation with the Department of Water Affairs, Forestry, and Environmental Conservation, all possible alternative sources of water."

"In this regard, an increase in rainfall as a result of artificial stimulation, should it be possible, will probably constitute the largest and most economical contribution."
WRC Annual Report (1978)

By 1980, two rainfall-stimulation experiments, one based at Bethlehem and one in Nelspruit, were initiated. The focus for the WRC was on the hydrological effects of rainfall stimulation, i.e., in the possible increase of water yield (in the form of river flow) in the study catchments. The research was initially focused on developing methods to stimulate rainfall and its associated approaches, rather than assessing whether or not this was being achieved and was conducted as two separate experiments (Mather and Morgan, 1990*).

By 1990, the two facets of the research had been merged to form the National Precipitation Research Programme, jointly funded by the WRC and the South African Weather Bureau. Facilities existed at Bethlehem, Carolina, and Nelspruit but concerns were being raised about the costs of the research versus its potential benefits. The preceding projects had demonstrated the ability to modify clouds, and new flares were designed that release hygroscopic salt particles during burning (Simpson Weather Associates and Kansas International Corporation, 1988*). The results, although seemingly robust for individual cloud-seeding events (Figure 2), had yet to produce convincing evidence that significant increases in areal rainfall could be achieved and whether this could be translated into increases in runoff Görgens and Rooseboom, 1990*).

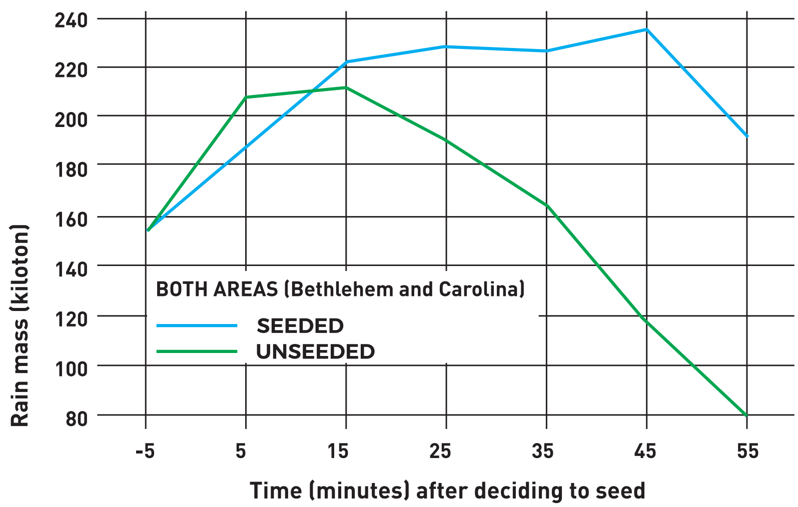


Figure 2. Reported responses in rainfall to seeding at the Bethlehem and Carolina research stations, South Africa (WRC Annual Report, 1990)

Relative to other projects, the costs were very high and a significant portion (sometimes more than 25% of the annual research budget) was spent on the programme (Figure 3). The list of equipment was certainly impressive and included four aircraft! (Box 1).

Box 1: NPRP Equipment

The combined equipment inventory for both projects was impressive and made the NPRP one of the best-equipped, convective cloud research groups in the world at the time.

A partial list of this equipment included:

- a Learjet 24, instrumented for cloud physics research, with dry-ice-seeding capability
- a Turboprop Aero Commander 690 (JRA), instrumented for cloud physics research and rainfall measurements at cloud base
- a Turboprop Aero Commander 690 (JRB), instrumented for cloud physics research with dry-ice-seeding capability and equipped with wing racks for end-burning flares
- an Aero Commander 500S (IZN) instrumented for making measurements of rainfall at cloud base, with isokinetic particle sampling capability

- a twin Commanche used for communication flights
- a 5 cm meteorological radar with a 1° beam width and volume scan capabilities (Bethlehem)
- a 5 cm meteorological radar with a 1.6° beam width and volume and sector scan capabilities (Carolina)
- a mesoscale network of rain gauges and automatic weather stations
- upper air sounding equipment at both sites
- aircraft maintenance and hangar facilities.

Each radar was supported by a computer system which displayed, digitised, and recorded the reflected radar signals. Each radar tracked the project aircraft, displaying (for the purposes of control) and recording the position of the aircraft. Each aircraft was equipped with a computer that displayed and recorded the aircraft measurements. Both the radar and aircraft data were further processed and stored in databases by macro-computers. The data bases were accessed for study purposes by cloud physicists at both sites. In the process, valuable analysis software was created.

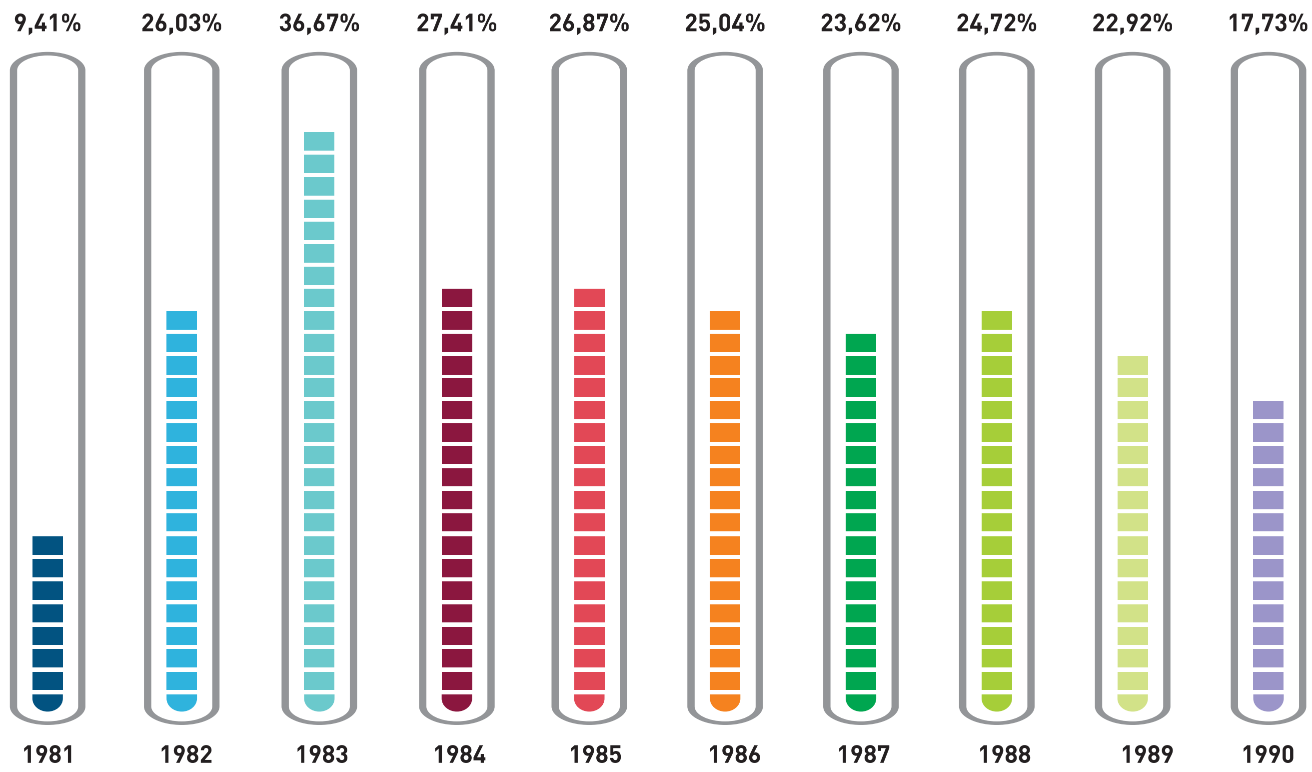


Figure 3. Proportion of WRC research funding spent on the National Precipitation Research Project (1981–1990).

The Bethlehem (South Africa) experiment was the most advanced and, in addition to radar systems used to estimate precipitation mass, included a comprehensive rainfall network of more than 100 recording rain gauges and the establishment of gauging stations for the monitoring of streamflow in the catchments which formed part of the experimental setup (Terblanche et al., 2001*). An analysis by Görgens and Rooseboom* (1990) and their recommendations led to the development of an extensive set of techniques to assess the efficacy of cloud seeding. The experiments conducted between 1991 and 1997 using this protocol suggested that seeded storms translated into an average increase of between 20% and 48% in the mean annual runoff of 13 different catchments over the eastern Highveld and escarpment (Howard and Görgens, 1994*; Mather et al., 1993; 1997*). By 1994, however, the WRC had warned that significant results of improvements in runoff response should be shown if funding were to be continued (WRC Annual Report, 1995*). With new priorities for the WRC emerging and no clear evidence of improved runoff responses, in 1998 it withdrew its funding from the National Precipitation Research Programme (NPRP). The initiative and its equipment shifted to a private entity and funding, but did not last much longer, although in 2005, it was awarded the United Arab Emirates International Prize for Weather Modification.

While cloud seeding and the associated equipment were the focus of the initiative, arguably, the secondary impacts and benefits associated with understanding spatial patterns of rainfall, radar assessment of rainfall, and the development of rainfall surfaces have endured to become important for the South African hydrological community and water resources management in general. However, it should be noted that the erstwhile NPRP programme was lauded internationally, and its results are often cited in ongoing international rain enhancement studies and applications.

Hydrometeorology and evaporation studies

Other hydrometeorological studies intended *"to enhance and develop understanding of the spatial and temporal characteristics of precipitation in Southern Africa; to characterise, understand, predict, and where possible, ameliorate the impact of weather and climate on the demand for and usage of water, and to develop weather and climate forecasting tools urgently needed for the better management and more effective utilisation of Southern Africa's water resources"* have been funded by the WRC. However, this was a relatively poorly supported section of research, attracting less than 3% of the Commission's funding in the 1980s and 1990s, although much of the research did overlap with that done in catchment hydrology.

In 1982, the water resources community requested the WRC to initiate research into the revision of the 1:250 000 average annual rainfall map series. Reports on drought occurrence in the country (Adamson and Zucchini, 1984*) and on ***Mapping mean annual and other rainfall statistics over Southern Africa*** (which was extended to include monthly statistics) (Dent et al., 1989*) were the precursors of efforts that included routines for the patching of monthly rainfall (Pegram et al., 1997), models of daily rainfall (Seed, 1992*; McNeill et al, 1994*), the development of daily rainfall surfaces for the country (Lynch, 2004*), estimates of daily rainfall using radar and rain gauges (Pegram and Clothier, 1999*; Clothier and Pegram, 2002*), and subsequent improvements to the mapping of daily rainfall surfaces (Pegram et al., 2006*; Pegram et al., 2016*).

Estimates of specific rainfall amounts over specific lengths of time ('design rainfall depths') are used to produce 'design floods', i.e., a hypothetical flood applied to inform the design of agriculture and roads infrastructure and water resources supply systems. Initially, the WRC supported research to produce design rainfall depths for durations of one day and longer on a national scale for over 2 000 stations in South Africa (Adamson (1981*). Subsequently, studies to improve these estimates and to provide updated one- to seven-day Depth-Duration-Frequency (DDF) relationships for South Africa (Smithers and Schulze, 2000*) and regionalisation of these estimates for flood estimation (Smithers and Schulze, 2003*) were supported.

Catchment/Surface hydrology

"Are we going to put all our energy in just measuring what happens, or shall we put a little more effort in research to try to find out why things happen?"
Penman critique of South African hydrology catchment experiments at the Empire Forestry Symposium in 1967 (Sopper and Lull, 1967)

The impact of land use and land cover on the country's water resources have been a focus of attention since the 1920s, when concerns raised by farmers about the impact of commercial afforestation on water resources came to the fore. At the time of the formation of the WRC, attention had moved away from purely commercial afforestation and had evolved more broadly to the effect of agricultural land use and catchment management on the water resources of the country, concomitantly prioritising hydrological research funding to the 'effect of catchment utilisation and the management of runoff'.

Recognising the risk of a disjointed approach to hydrological research and given the strong history and well-established role of many government departments and other state entities (such as the South African Forestry Research Institute and several universities), the Coordinating Committee for Research on the Hydrological Cycle (CCRHC) was established jointly in 1977 by the WRC and the Department of Water Affairs, Forestry, and Environmental Conservation. Prof John Hewlett of the School of Forest Resources (University of Georgia, USA), who had previously visited South Africa as an advisor on the paired catchment experiments and afforestation research, played an important role as a consultant. At the time, the committee identified 53 research projects that could be considered "hydrological research work". Of these, 34 were undertaken by government departments (mainly Water Affairs, Forestry, Transport, and the Weather Bureau) while the remainder were undertaken by different universities, mainly the universities of the Witwatersrand and Natal.

At that stage, the WRC directly or indirectly supported 14 of these projects by providing either funds or personnel. The Pitman model had been released in 1973, but the presiding sentiment was that this (and some of the related models) would have to be modified and refined to be applicable to small catchments. This led to the establishment of numerous small catchment studies.

Catchment and process studies

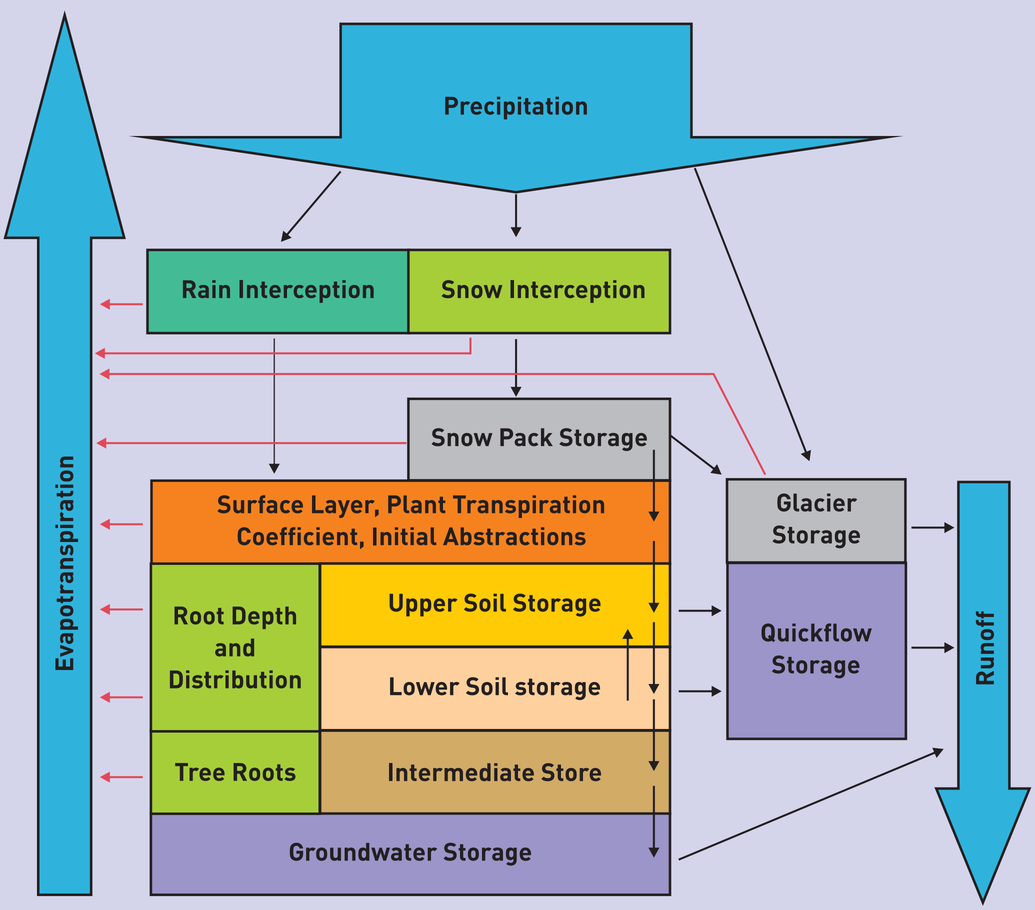
By 1980, the WRC had initiated 15 projects under the surface hydrology theme, with seven having been completed. A significant focus of these was rural catchments and several experimental catchments had been established. These included the Ecca, Beaufort, and Wilderness catchments which were supported by projects run by the fledgling Institute for Water Research at Rhodes University; the Cedara, De Hoek, and Ntabanhlope catchments supported by the Department of Agricultural Engineering at the University of Natal; and two small catchments in Zululand, supported by the University of Zululand. Mindful of the 1973 Penman critique, hydrological process studies, rather than just rainfall-runoff responses, began to evolve.

Concomitantly, several flood studies associated with these rural catchments were underway and the scope of the studies inevitably moved beyond the simple rainfall-runoff responses and included aspects of the areal distribution of rainfall, the influence of topography and vegetation on soil moisture distribution, hydrological studies of soil loss with particular emphasis on rainfall erosivity, and a study of potential flood producing rainfall in Natal (Schulze, 1982). From the initial focus on small rural catchments, the WRC began to support research on flood generation to assess flood estimation techniques (Van Schalkwyk et al., 1985*; Campbell et al., 1987*) and their evolution into more sophisticated approaches, which included statistical (Van Bladeren et al., 2007*) and more process-oriented approaches which considered antecedent moisture conditions at catchment scale (Smithers et al., 2007*). Since 2007, flood-related research has received intermittent support from the WRC, but in 2018, in collaboration with several other organisations, the National Flood Studies Programme (http://www.nfsp.co.za/) has received some support.

Despite the intended emphasis on small catchment design floods, the early 1980s were dominated by severe droughts, which led to a change in emphasis of existent studies. A study led by Prof Roland Schulze of the University of Natal was seminal in this regard (Schulze, 1984*). Not only did the work improve the United States Geological Survey (USGS) Soil Conservation Services (SCS) design flood model, but it also included improvements to the antecedent soil-moisture routines, and a classification of South African soils for hydrological modelling purposes (Dunsmore et al., 1986*). Schulze's study initiated the evolution of the Agricultural Catchments Research Unit (ACRU) model into its current form as a multi-purpose, daily-timestep hydrological modelling system (Box 2).

Box 2: The ACRU Agrohydrological Modelling System

The ACRU model evolved from a study of catchment evapotranspiration carried out at Cathedral Peak in the early 1970s (Schulze, 1975). ACRU originally stood for the Agricultural Catchments Research Unit within the former Department of Agricultural Engineering of the University of Natal in Pietermaritzburg – although it has now become a generic name for the model and the system within which it is operated: https://cwrr.ukzn.ac.za/resources/acru/. The agrohydrological component of the model evolved from research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1983). Through the strong support of the WRC in the 1980s the model has continuously developed and ACRU4 is now in use. Various enhancements to the ACRU model have been made to extend its useability. The first major advance was its conversion to a distributed version (Schulze et al., 1989) and then into improved efficiency in terms of its computer science (*Lynch and Kiker, 2001). More practical functionality was added to include options to simulate runoff response from urban areas (*Schmidt and De Villiers, 2001) and water quality through the ACRU-NPS for the generation and transport of nitrates, phosphates and sediment (*Lorentz et al., 2011) and ACRU-Salinity (*Kamish et al., 2008). Updates to the model and its user manual have taken place regularly (Schulze, 1989;1995; Smithers and Schulze, 2004).



Structure of the ACRU Agrohydrological Modelling System (Schulze, et al., 1995).

As computing power increased and instrumentation moved from analogue to digital platforms, hydrological process studies adjusted. The traditional paired-catchment experimental design slowly disappeared and more single catchment experiments with more sophisticated instrumentation were established. These included new experiments in the Two Streams and Weatherley catchments, the former focusing on the effects of ***Acacia mearnsii*** (a dominant invasive alien plant in the eastern part of the country) and the latter on water-use associated with ***Eucalyptus grandis,*** which had been relatively under-studied at the time. Although the focus was still on forest-hydrology studies, the experimental design and the new instrumentation available in these new studies were far more comprehensive than the original paired-catchment experiments and focused on elucidating the components of the hydrological cycle and the interactions among them. This led to several interesting findings and applications, which are discussed in the next section.

With funding for fundamental studies increasingly difficult to find, the historical research catchments were eventually closed down. Of the original catchments, only Jonkershoek (in the south-western Cape) was still active and then, only on a skeleton basis. Nevertheless, the value of the data that were collected from these catchments was still recognised. Comprehensive re-analyses led to new insights into the impact of different levels of forestry, different growth rates, and different site characteristics (Scott and Le Maitre, 1998*; Scott et al., 2000*). From 2012–2015, the core Jonkershoek and Cathedral Peak catchments were resurrected with base funding from the South African Earth Observation Network. The WRC projects that followed have built on this infrastructure; the Cathedral Peak and Jonkershoek sites have been re-established as very effective living laboratories with a strong focus on developing postgraduate student capacity (Toucher et al., 2016*).

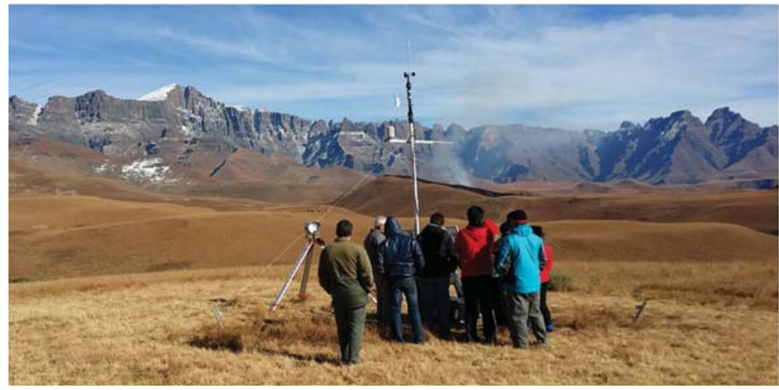


Figure 4. Postgraduate students examine various monitoring instruments at Cathedral Peak Catchment VI. (Credit: UKZN)

Impacts of land use and land cover on the hydrological cycle

As can be seen from the focus of the catchment studies described above, land use and land cover change have been focal areas of research for the WRC since its inception. Originally, this was on the impact of stream flow from paired-catchment experiments, but a need for more rapid generation of results and a corresponding evolution in microcomputing facilitated the instrumentation and monitoring of different aspects of the hydrological cycle. This included instrumentation for the measuring of total evaporation (often termed evapotranspiration and composed of the transpiration by plants and evaporation from vegetation, soil, or open water surfaces), and improvements in soil moisture monitoring (Savage et al., 1997*; Savage et al., 2004*; Mengistu et al, 2013*).

Results of these experiments (Figure 5) led to better understanding of the role of tree physiology in the transpiration process (Dye et al 2008*; Jarmain et al., 2009*), the link between transpiration and soil moisture (Gush and Dye, 2009*), identified factors controlling rates of interception from canopies (Bulcock and Jewitt, 2009), the important role of shallow groundwater on hill slopes in generating low flows and the interaction between surface and groundwater flows (van Huyssteen et al., 2005*; Lorentz et al; 2008*), including in riparian areas (Everson et al., 2008*), and the impacts of land use and land cover change on these hydrological processes (Clulow et al., 2011*; Jovanovic et al., 2014*).

Figure 5. Monitoring of transpiration with the heat pulse velocity system and canopy interception at Two Streams research catchment.

Biofuels and bioenergy crops have been a particular focus of the WRC. Research on the impact of growing crops for biofuels on water resources at a catchment scale and has been funded through the 'Agricultural Water Management' focus area of the WRC, rather than through 'Catchment Hydrology'. Apart from sugar cane, no biofuel and bioenergy crops have been identified as having a significant, long-term impact on water resources (Jewitt et al., 2009b*; Kunz et al., 2016*).

An aspect of hydrological research that has come to the fore since the late 1990s has been the impact of invasive alien plants (IAPs) on the country's water resources (Versfeld et al., 1998*). In collaboration with the Department of Environmental Affairs (in various forms), water use by alien trees has been the subject of numerous studies and, apart from highlighting the detrimental effect of IAPs on water resources, has led to the testing and application of numerous innovative monitoring approaches, largely through the efforts of the Council for Scientific and Industrial Research (CSIR) (Everson et al., 2008*; Clulow et al., 2011*; Dzikiti et al., 2018*). Concomitantly, it was realised that water-use by the country's natural vegetation had been under-studied – an important knowledge gap, since water-use by the natural vegetation forms the baseline against which water use by different land-use types is assessed and provides the equivalent of "naturalised" flow which is an important aspect of South Africa's water resources planning approach. This realisation led to two major studies which provided improved estimates of the vegetation types recognised at the time (Dye et al., 2008*; Gush and Dye, 2015*) and an ongoing reclassification based on the updated vegetation types recognised by Mucina et al. (2006).

Although these studies have greatly enhanced research on catchment hydrology, the biggest advances in improving the estimates of total evaporation have been through the agricultural meteorology groups at the CSIR and University of KwaZulu-Natal and were funded through the 'Agricultural Water Management' focus of the WRC. Nevertheless, there is significant overlap with this work and that in the research catchments, as experiments often took place at the aforementioned research catchments. Results from these and other sites have been applied to estimate evaporation at a catchment scale from different land uses and land covers including commercial afforestation, sugar cane, and various potential biofuel crops.

The information and knowledge from these studies has been applied in improved hydrological modelling in some of the revised streamflow reduction activity (SFRA) licensing (Gush et al., 2002*; Jewitt et al., 2009a*) (see Figure 6) and biofuel assessment tools (Jewitt et al., 2009b*; Kunz et al., 2015*), as well as being extensively utilised in applications supporting the Working for Water program (Le Maitre and Görgens, 2003*).

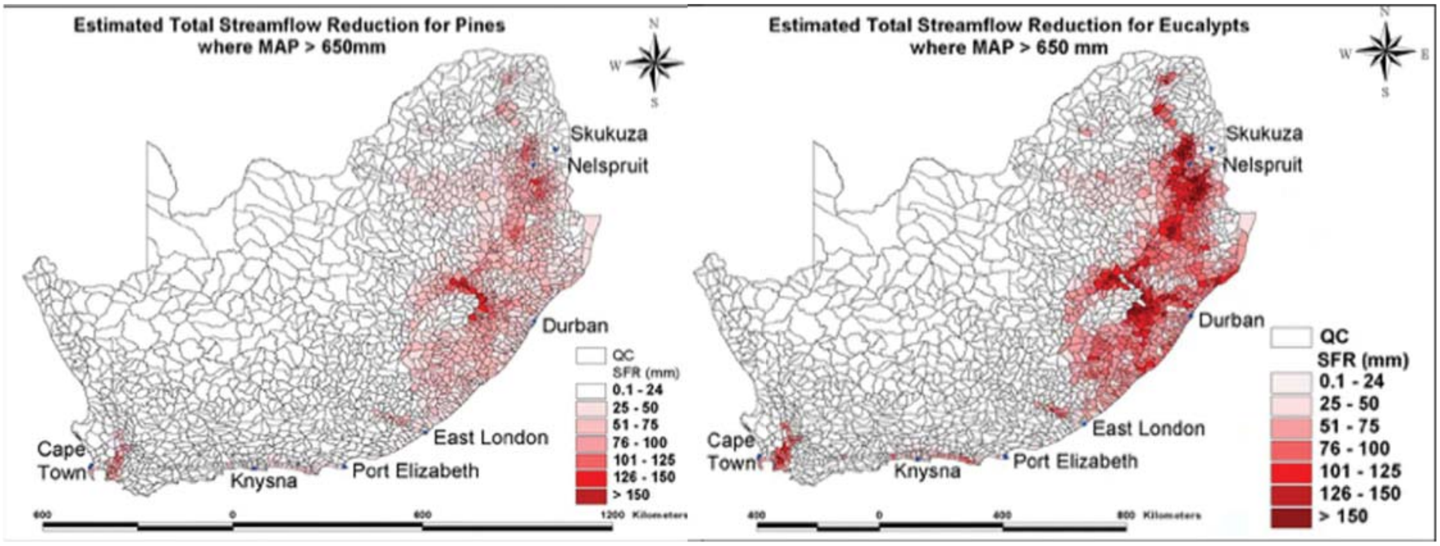


Figure 6. Estimated annual reduction in streamflow from Pines and Eucalyptus in South African quaternary catchments (Gush et al., 2002*).

Given the surface area of the country covered by reservoirs and South Africa's reliance on inter-basin transfer schemes, evaporation from open water surfaces has been the subject of a few, but very significant, studies. These include evaporation from dam surfaces (Savage et al., 2017), but also two extensive studies and assessments of transmission losses (evaporation losses from river surfaces and riparian vegetation) from the Orange River (Everson, 1999*; Mackenzie et al., 2004*) through which it was estimated that approximately 960 million m^3 was lost downstream of the PK Le Roux (Van der Kloof) Dam per annum. More recently, Dennis et al. (2012*) and Riddel et al (2017*) have highlighted the variability and complexity of the transmission losses in semi-arid systems. Linked to the implementation of EFlows, they explored the complexity of evaporative losses from the river surface and transpiration from riparian vegetation interact with a river system that may be either gaining water from shallow groundwater, or providing recharge, depending upon the flow conditions at the time.

Streamflow analysis

As a largely semi-arid country, the variability of flow in South Africa's rivers has always been of interest to hydrologists and water resources planners. Over the years, several studies have been undertaken to better understand this variability and its impact on our water resources.

These include the flood studies reported above, but also include various analyses of the flow regime, including an interrogation of different flow regime types across the country (Hughes and Munster 2000*; Hughes et al., 2011*) and baseflow separation studies which have sought to identify the link between groundwater and surface water (Hughes et al, 2007*; Tanner and Hughes, 2014). Aspects related to the understanding and management of low flows (including in ephemeral systems; Hughes, 2008*) have received particular attention (Smakhtin and Watkins, 1997*). Such analyses are closely aligned with the realities of managing South Africa's water resources and estimating the impacts of SFRAs (Jewitt et al., 2009a*) and the management of environmental water requirements from a hydrological perspective (Hughes and Munster, 2000*), as the periods of low flow are a critical aspect of environmental flows (Eflows).

Hillslope processes and soils

A more comprehensive understanding of the role of shallow groundwater and hillslopes in the generation of river flows in

South Africa has evolved over the last two decades. This has been closely linked to additional analysis of the runoff patterns in the aforementioned research catchments, but, similar to the advances in the estimates of total evaporation, hillslopes and shallow groundwater runoff has also benefited from instrumentation which is able to monitor spatial and temporal patterns of soil moisture. This has been particularly important in research at the Weatherley and Two Streams catchments (Lorentz et al., 2008*; Le Roux et al, 2010*; Everson et al., 2013*) and more recently in the Kruger National Park (Riddell et al., 2017*). These studies have highlighted the importance of understanding the role of soils in rainfall retention, groundwater recharge, and runoff generation and have illustrated the unique importance of shallow groundwater and hillslopes in generating and maintaining low flows in South Africa (Figure 7). The evolution of hydropedology and the revised classification of soils to support hydrological modelling and related applications in South Africa is a particularly useful outcome of these studies.

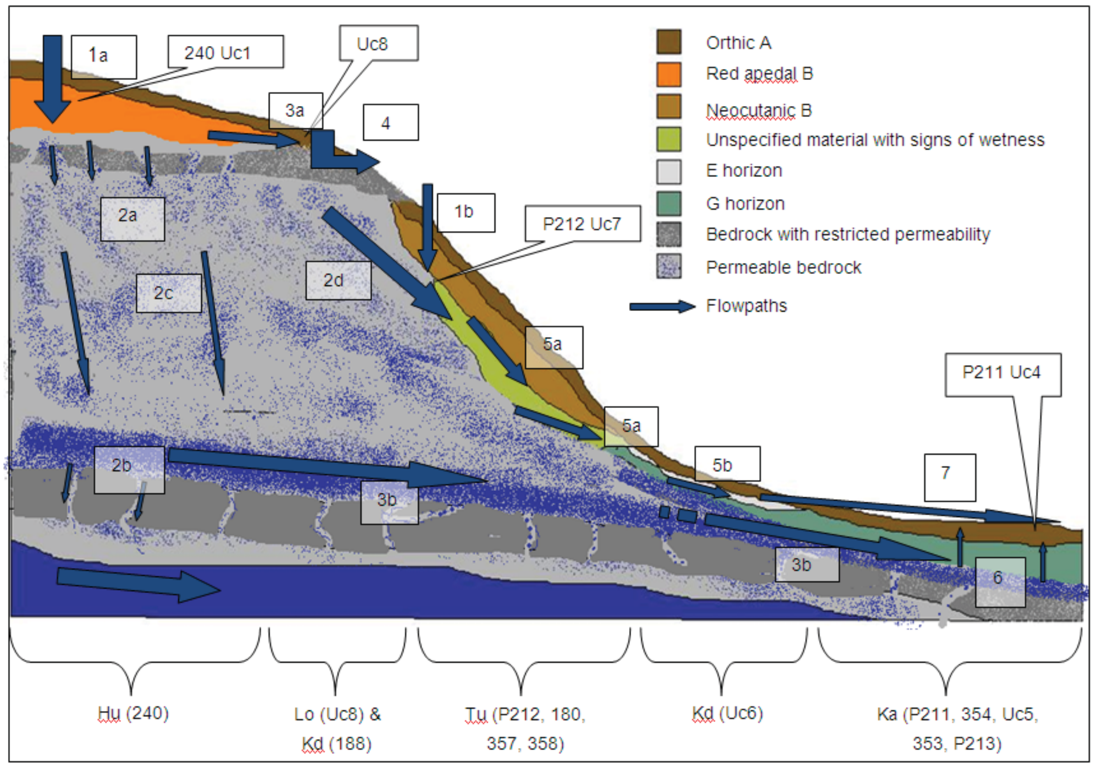


Figure 7. The relationship between soil type, hillslope and surface and groundwater at Weatherley (Le Roux et al., 2011*).

Hydrological modelling systems

The development of 'mathematical models' has been highlighted from their introduction across several research projects, not only in the field of hydrology. Output from watershed models is recognised as providing basic input to a wide range of other research and applied projects, including flood studies and floodplain management, land-use change, apportionment of water rights, determination of storage requirements and water resources allocation, reservoir operation, pollution studies and the design of spillways and roadways.

As computing power progressed, there was much interest in the development of hydrological models as adaptation of the manual estimates which were the norm at the time. Internationally, the first well-known hydrology model, the Stanford Watershed Model, was released in 1966. In South Africa, the Pitman model was released in 1973 (Pitman, 1973), but by the time the WRC was established (1971), the bulk of the work leading to its development had already been done. However, the WRC recognised research funding to universities as an important part of their strategy. The first Annual Report (1973) notes that funding of R10 000 was set aside for the "Development of mathematical models for the optimisation of systems for the development of water resources", which provided some support for the work in progress at the Wits Hydrological Research Unit. Development of hydrological modelling systems was funded entirely by the CSIR and Wits University at the time. The Pitman model continued to evolve, though much of the research was drawn from the group's application of the model to water resources planning and regular assessments of the country's water resources (Box 3 and Box 4).

Box 3: The Pitman Model

The Pitman Model is a monthly time step Pitman (Pitman, 1973) rainfall-runoff model which has been widely used for water resources assessments and more recently research in the southern Africa region. The model was originally developed by Bill Pitman as the focus of his PhD under the supervision Prof Des Midgley and used in the 1981 assessment of the country's water resources. Originally intended as monthly time-step model applicable at large catchment scale, the model has been widely applied to water resources assessments in South Africa and increasingly southern Africa over the past ten years. Development has largely been driven by practical and applied issues rather than being research driven. The Rhodes University Institute for Water Research has played a major role in more recent developments, such as the inclusion of a groundwater component for the model (Hughes et al., 2013).

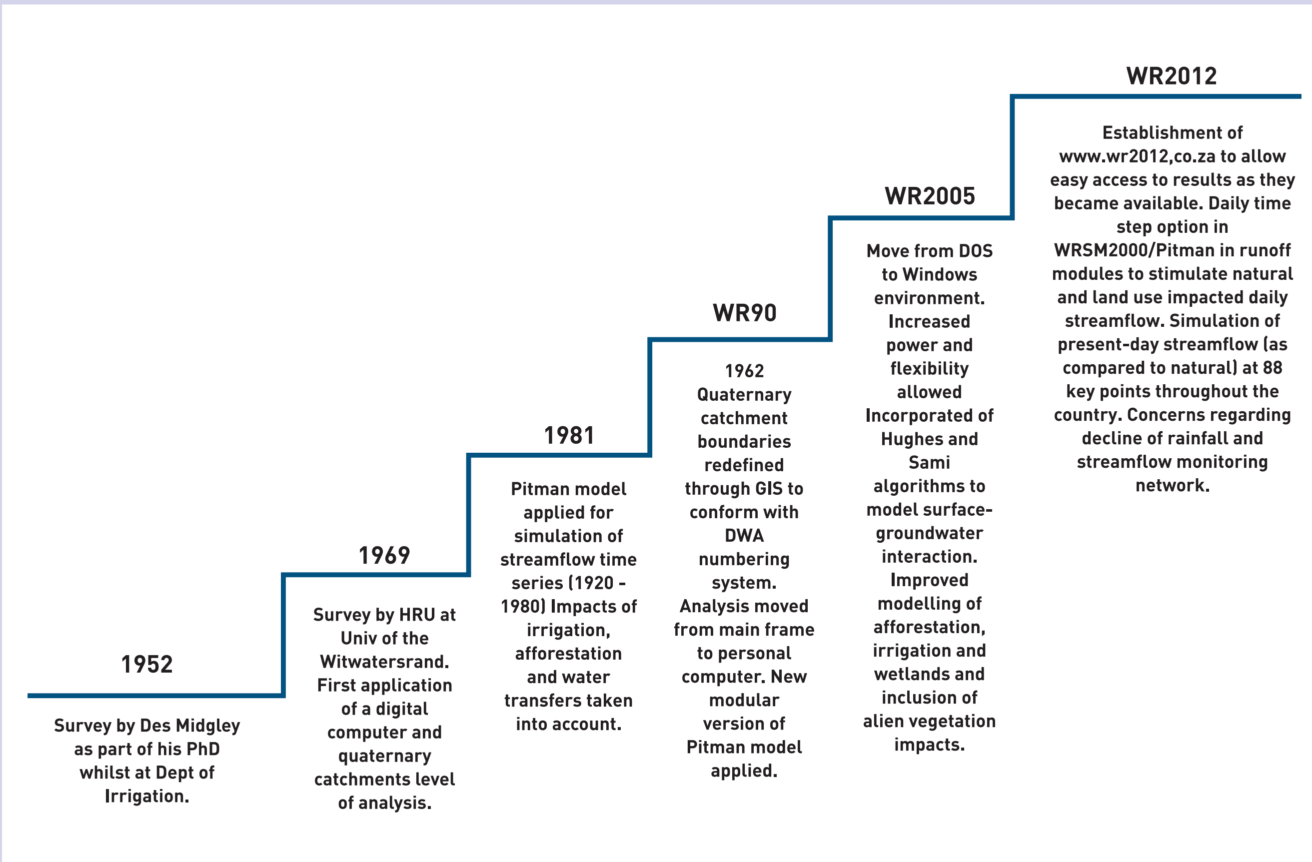
Figure 8. Hydrology Honours students from the University of KwaZulu-Natal during a field visit to Cathedral Peak. (Credit: UKZN/Water Wheel archives)

An assumption that drove much of the research supported by the WRC was that the Pitman model was not suitable for application in smaller rural/agricultural catchments and that specific work was needed to address land use and land-cover changes occurring in the areas represented by such catchments. Thus, the early focus was on the establishment and monitoring of research catchments where the complexities of land use and land cover change could be assessed, and hydrological models could reflect these impacts. In addition, small research catchments supported flood- and drought-related studies, facilitating the refinement of a number of important hydrological modelling approaches.

From a design flood perspective, the South African amendment of the USGS SCS model was an important

Box 4: History of Water Resources (WR) assessment studies in South Africa

Assessments of the state and availability of the country's water resources have taken place approximately every 1-12 years since 1952. The figure below summarises each of the assessments and the advances in approach to date.
See www.wr2012.co.za.



Sources: Pitman, WV 2011. 'Overview of water resource assessment in South Africa: Current state and future challenges' in Water SA 37(5), p 659-664 and Pitman and Bailey, 2016 Developments In Water Resources Appraisals Of South Africa, Lesotho And Swaziland (1952 To 2015). Presentation at launch event, March 2016.

initiative (Dunsmore et al.,1986*; Schulze, 1987;1995*) and one which, after several refinements, remains an important tool for practitioners in the country. In parallel with the development of SCS, the ACRU model was refined through the work done in these small catchments (Box 2). In the Eastern Cape, the catchments operated and supported by Rhodes University were important in the development and testing of the Variable Time Interval (VTI) model and were a precursor to some of the detailed streamflow analyses that were a focus of that group's activities in the 1990s (Hughes and Sami, 1994*), including the development surface water-groundwater interaction routines which were included in the Pitman model from 2005 (Box 3).

A key aspect of the development of these models was the intention to transfer the findings from the gauged experimental catchments to ungauged areas of the country.

Testing and assessing the uncertainty associated with these efforts was the basis of an important study completed jointly by Rhodes University and UKZN in 2010 (Hughes et al., 2011*).

After 1998, improved computer science approaches using available hardware and software led to some structural model improvements. Comprehensive modelling systems incorporated the models into broader decision support systems consisting of other data and analysis tools. The most comprehensive of these are the system for Spatial and Time Series Information Modelling (SPATSIM) and ACRU Agrohydrological Modelling systems, although there has been some effort to combine these in the Hydrological Decision Support Framework (HDSF) (Clark et al., 2012*). The role of the modelling systems has been integral in decision making and planning, particularly in the implementation of the SFRA aspects of the National Water Act (NWA) of 1988, implementation of the Reserve and EFlows, and in estimates of the impacts of climate change on the country's water resources.

Simultaneously, the opening of the country to international collaboration preluded a proliferation in hydrological models in the country. The support of hydrological modelling efforts by the WRC was certainly effective with the Pitman and ACRU models leading to their extensive use by South African hydrologists. While competition between the different modelling groups may have stimulated improvements, one could argue that the South African hydrology community is too small to support the development and maintenance of more than one model and its associated 'ecosystems'. A consolidated and collaborative effort in development and application may have supported a more sustainable national model.

Data, monitoring and computing

From the outset, the WRC felt that there was wealth of information could be garnered if hydrological records of government and other departments were available digitally, stating:

"the efficient utilisation and management of the Republic's water sources, <and> the collection and processing of reliable data with reference to the hydrological cycle, is of key importance. Although this function is already performed on a continuous basis by various Government Departments for internal purposes, it is clear from the Commission's water research survey that a mass of potentially useful data lies stored away in records. If this information is processed into useful form, it can gainfully be incorporated into numerous important task areas of water research and development." (WRC Annual Report, 1973)

At the time, rainfall and runoff data were stored on charts that had to be manually digitised. By 1982, a national data bank of digitised rainfall records was developed by the South African Weather Bureau through a contract between the Department of Transport and the WRC. This was developed in close collaboration with a similar project undertaken by the Department of Agricultural Engineering at the University of Natal, which had initiated the digitising of rainfall charts from (KwaZulu) Natal, a process that eventually extended to cover the rest of the country (WRC Annual Report, 1980). Through cooperation with the DWAF, this data bank was extended to runoff records.

In 1986, the WRC, in collaboration with the then-IBM computing company and the University of Natal, established the Computing Centre for Water Research (CCWR) as a "numeric information system" (WRC Annual Report, 1986). The mission of the CCWR was:
"To support water research in South Africa by providing a national, computer-based information system that would:

- enhance the transfer of data and results
- provide a facility for multidisciplinary research
- provide alternative computer facilities."

For many years, the CCWR was an invaluable resource for researchers looking for good quality hydrological and related data in the country. However, when the NWA was implemented, the CCWR shifted its mandate towards facilitating collaboration between researchers. Arguably, there was an over-emphasis on new efforts, such as the stimulation and motivation of, and the provision of incentives and support for water researchers rather than the core data provision functionality. Particular software systems, data management approaches, and protocols were promoted and even enforced. Consequently, its core users began to feel a loss of autonomy and freedom of choice, and even interference in their work. Ultimately, users felt that the core functions of the CCWR were lost and that the new focus was tangential to their needs. By 2002, the CCWR had lost support of its users, its host, and its funder and was closed down, leaving a gap that is still felt by the country's hydrological researchers.

The decline in the country's rainfall and runoff monitoring networks from the perspectives of both water quantity and quality has been a source of concern for hydrologists for many years. The WR2012 study and an associated paper (Pitman, 2011) illustrate this dramatic decline since the monitoring peak in the 1980s (Figure 9). This decline continues. Rainfall data, which used to be freely available, are now only available by payment through a Dutch company and the runoff data, although freely available from the Department of Water and Sanitation (DWS) website, are rarely available because of problems with the data management system and the DWS internet platform. The core DWS laboratory at Roodeplaat (Gauteng) lost accreditation and the associated water quality monitoring programmes are mostly defunct. Simultaneously, however, interest in data sourced by remote sensing has been increasing.

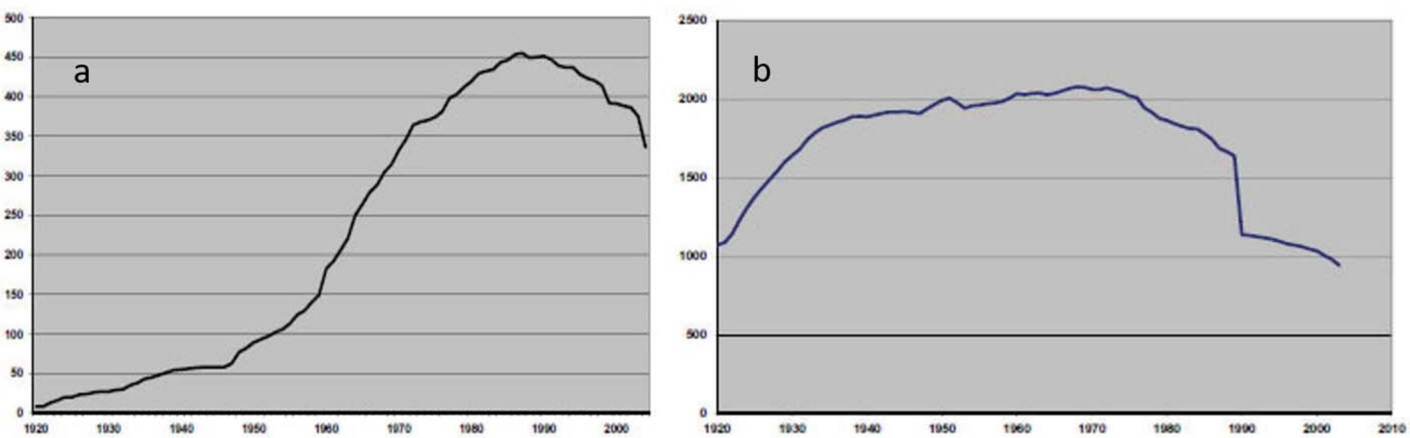


Figure 9. The WR2012 study on water flow (a) and an associated paper (b) on the number of rainfall gauges (Pitman 2011) illustrate the dramatic decline in monitoring of water flow and rainfall since the monitoring peak in the 1980s.

The WRC has supported research into the use of remote sensing data for approximately the last 15 years, although not in a fully cohesive manner. A recent review (Makapela et al., 2015*) highlighted the opportunity for remote sensing products to fill some of the monitoring system gaps, but more significantly, to provide estimates for parts of the hydrological cycle, e.g., soil moisture (Sinclair et al., 2012*) total evaporation (Jarmain et al., 2009*) and rainfall (Pegram et al., 2016*), which are notoriously difficult to measure at larger scales. However, these reports all warn – and this is something that many seem not to understand – that estimates from remote sensing are neither data nor measurements. They are effectively modelled outputs and subject to the same uncertainties as any other hydrological model: they are not direct measurements of a flux or a process.

Spatial databases

Since the 1980s, increasing computer power has led to the emergence of Geographical Information Systems (GIS) and spatial databases as important hydrological tools. Hydrologists were quick to recognise the importance of representing the spatial dimension of the data and developed systems to include these, such as SPATSIM and HDSF (as described in the section on hydrological model development). A particular aspect of these systems was the transformation of the agrohydrological atlases that were first published in the 1970s and 1980s into far more sophisticated spatial information systems. The quaternary catchments database (Schulze and Maharaj, 2004*) is the most comprehensive of these and includes estimated values for corrected daily rainfall, temperature potential evaporation, land use, land cover, and actual soils for the entire country and formed an important basis for much of the hydrological work that was undertaken, although this was largely developed through the Agricultural Water Management KSA. This database has provided the modelling foundation for many climate change studies but is also the basis for assessment of many of the impacts of land use and land cover on the hydrological cycle, including commercial afforestation, biofuels, and different agricultural crops, as described in that section.

The 'Waterlit Collection'

A somewhat related and important initiative of the WRC was the collation of the 'Waterlit Collection'. This is a collection of articles, reports, and academic publications which were collected and managed at the CSIR in Pretoria from 1974 until the mid-1990s under the auspices of the South African Water Information Centre, with the support of the WRC (1990). The collection formed part of a strategy through which South African water scientists, internationally isolated at the time, attempted to secure the latest scientific information related to all fields of water resources management from all over the world. By 1999, the collection contained more than 300 000 items, making it one of the largest databases of its kind and highlighting how important investment in water knowledge was felt to be at the time.

The collection evolved from a paper-based to a digital, and then an online catalogue, after which the internet and South Africa's return to the international arena signalled its redundancy. The collection now forms part of the South African Water History Archival Reports Tree at North West University, Potchefstroom (Tempelhoff, 2015).

Support to the NWA

In the mid-1990s, a new National Water Act was imminent and there was an associated shift in the focus of hydrological research. Although some of the process studies continued and were still considered important, the real focus was now on the role that hydrology and hydrological models could play in supporting the implementation of Integrated Water Resources Management, which was a key component of the new Act. South Africa's history of research into the impacts of land use on water resources provided for some unique aspects of the NWA.

For many decades, there had been acceptance in South Africa that commercial afforestation causes a reduction in streamflow. By 1972, a permit was required to afforest land with exotic tree species. There has been ongoing research on this issue since 1972, but also much interest and research into other aspects of land use and land cover on water resources. The White Paper that preceded the NWA included what became Principle 18 of the 1998 Act: ***"Since many land uses have a significant impact upon the water cycle, the regulation of land use shall, where appropriate, be used as an instrument to manage water resources within the broader integrated framework of land use management"***.

In 1998, Principle 18 was given effect in law as a stream-flow-reduction activity, which is defined as ***"… any activity (including the cultivation of any particular crop or other vegetation) … [that] … is likely to reduce the availability of water in a watercourse to the Reserve, to meet international obligations, or to other water users significantly"*** (NWA Section 36(2)). The principle and its inclusion in law reflect the extensive hydrological research undertaken in the country since the 1950's, and the subsequent supported by the WRC since its inception. To date, many crops have been investigated as potential SFRAs. Of these, only dryland sugar cane in the KwaZulu-Natal Midlands is regarded as a potential SFRA, but there is no clear argument yet for the declaration of annual crops, including potential biofuel feedstocks, as SFRAs (Jewitt et al., 2009b; Kunz et al., 2015).

Education

The evolution of the WRC and the international recognition of hydrological research occurred simultaneously. In the late 1970s and early 1980s, there was much debate about hydrology as a science, with many philosophical and conceptual papers emerging at the time. A particular feature was that hydrologists were drawn from many disciplines, which resulted in a lack of both coherence and conceptual foundations in applications, a consequence many believed to result from a lack of a common educational approach. In 1984, an undergraduate degree in Hydrology had begun at the University of Natal and another degree at the University of Zululand was soon to follow.

Both degrees were closely associated with and supported by WRC projects in terms of both staff involvement and student support. In later years, undergraduate hydrology programmes at the University of the Western Cape and University of Venda were established, together with strong postgraduate research programmes. Postgraduate hydrological research took place at many other institutes but in particular at Rhodes University and different units of the Universities of the Witwatersrand, Stellenbosch, and (Kwa-Zulu) Natal. Members of the hydrology community play a major role in the assessment of Professional Natural Scientist (Pr.Sci.Nat.) applications in the water resources management field of practice, as most of the mentors and referees are graduates of these programmes. The strong focus on capacity development by the WRC since 1994 has been well served by the strength that was built in these institutions and in the discipline of hydrology.

International relations

In 1982, the South African National Committee for the International Association of Hydrological Sciences (SANCIAHS) was established and has organised biannual symposia ever since. SANCIAHS was established under the auspices of the IAHS and has an international mandate through South Africa's membership of the International Union of Geodesy and Geophysics (IUGG) via the South African Department of Science and Technology (now the Department of Science and Innovation). The Committee coordinates and contributes to international hydrology research-related activities and organises biannual symposia. The WRC itself, as well as the research it supports, has always featured strongly at the symposia and has effectively played host (and often coordinator) for the South African IAHS network. A feature of the SANCIAHS symposia has always been that they are reasonably priced and convenient to attend, providing a user-friendly opportunity for postgraduate students to make their first conference presentations.

South African hydrologists have enjoyed a relatively high international profile over the years. The input of the famous forest hydrologist, John Hewlett, in guiding the paired catchment experiments and early hydrology research themes was critical. Des Midgley was well respected internationally, despite the isolation of the apartheid and cultural boycott era. In 1996, he was awarded the International Hydrology Prize. Twenty years later, in 2016, Prof Denis Hughes, who served for many years as an IAHS vice president, was awarded the International Hydrology - Volker Medal for his outstanding contributions to promoting the science and practice of hydrology in sub-Saharan Africa. In collaboration with the SA Society of Civil Engineers, the Des Midgley Memorial Lecture is held as a keynote address at every SANCIAHS symposium.

In addition, South African hydrologists and the WRC have supported many of the initiatives of the United Nations Educational, Scientific, and Cultural Organization (UNESCO) International Hydrology Programme (IHP). These have included the well-known FRIEND (http://www.unesco.org/new/en/natural-sciences/environment/Water/ihp/ihp-programmes/friend/) (Hughes, 1997) and HELP (https://en.unesco.org/themes/water-security/hydrology/programmes/help) initiatives. Both of these have highlighted South African hydrological research internationally and relayed ideas and perspectives to explore in the South African context.

In many ways, the international collaboration established by the IAHS and the UNESCO IHP was critical in rapidly exposing South African hydrologists to their international counterparts after 1994. Through these networks, the hydrological research community rapidly and effectively interfaced with international funding initiatives and was soon supported by several international funders, including the European Union and the Carnegie and Rockefeller foundations. Expansion of research in other southern African countries and the concomitant increase in postgraduate students leading to the reality that hydrological research funding was now available principally through these international programmes, rather than the WRC.

Concluding thoughts

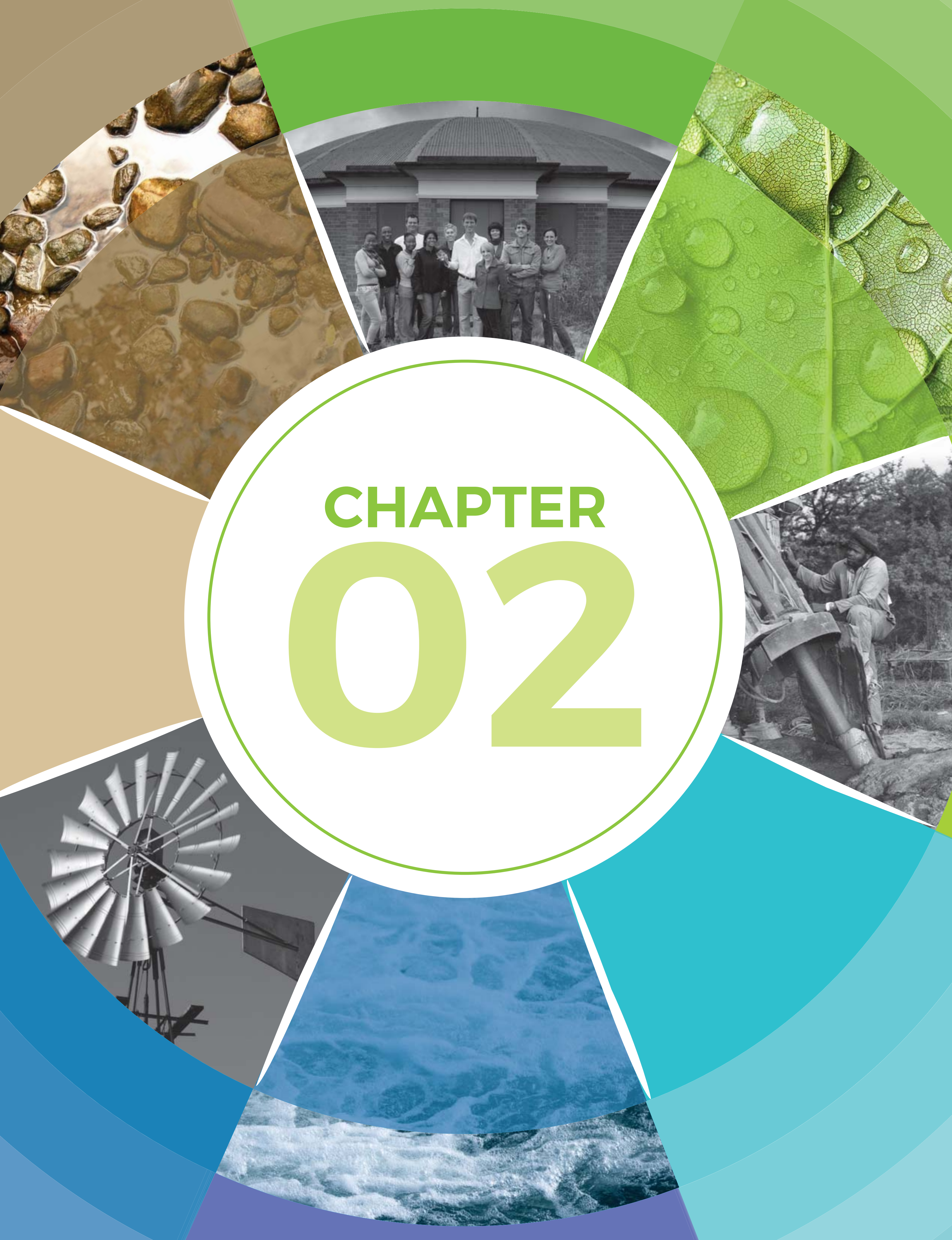
Over the past 50 years, South African hydrologists have built on the strong reputation that preceded the establishment of the WRC. The research catchments are well known and several of the scientists have a strong international profile. However, it could also be argued that there is a wealth of knowledge confined to the numerous WRC research reports and that South African hydrologists (with one or two exceptions) have not really been effective in publicising this work in international journals. Furthermore, an unfortunate consequence of the isolation era was strong competition within and between the different groupings of South African hydrologists. Whilst competition is healthy in some regards, perhaps South Africa's hydrological development has been compromised by these strongly competitive approaches and would have benefited from a far more collaborative empathy between its very strong scientists.

After 1994, South African hydrologists responded strongly to the new research environment and were heavily involved in many of the new research projects in more of an applied setting. Ironically, in 2010, the international hydrological community began to realise that hydrological science viewed role of society in water resources management as peripheral. To South African hydrologists, this was nothing new, having been exposed to this reality for the preceding ten years.
The nature of the education programmes and the exigencies of the South Africa's research environment has meant that collaboration with scientists from other disciplines has been a strong feature of South African hydrology for at least the past 20 years. Initially, this might have been with other scientists from the biophysical fields (such as aquatic ecology, geomorphology, soil science, and to some extent, economics), but over the past ten years, the association has moved into a more active collaboration with social and other human scientists. Collaboration with industry partners and government departments has always been a strong feature of South African hydrology research and the role of the WRC project steering committees and reference groups has been critical in maintaining that contact and ensuring that research products are actually applied in consulting practice, water-related policy development, and in water resource assessments and the decision making that arises from these policies.

Nevertheless, there are some concerns for the future. These include the continual shrinking of the research funding that is available to support the core disciplines as the focus towards implementation becomes stronger. It is very difficult for a discipline like hydrology to produce marketable and commercial goods, which often seems to be the criterion of support. The water resources management value chain is very long and starts with an understanding of the hydrological cycle. Because the hydrological cycle is early in the value chain and not at the end, there is a risk that the funding is focused only on the end products of this value chain and is not distributed effectively throughout it. A further concern is the decline in the water quantity and quality networks throughout the country and indeed, internationally. Remote sensing, citizen observations, and the ongoing evolution of smart sensors, inter alia, all provide opportunities to address this and even enhance current monitoring approaches. However, core observation data and strong laboratories are imperative in providing validation and calibration for these new techniques and approaches.

Although there are strong educational institutions and good degree programmes in hydrology, it has also been argued that this core epistemology is being diluted as the focus shifts towards applied water resources management; hydrologists become dilettantes, dabbling in other disciplines and neglecting the core focus of their science. Rather, the involvement of scientists and practitioners from different disciplines as true collaborators in projects and on research teams must be preferred to teams with shallow and only generalist skills. The challenge of multi-, inter-, and trans-disciplinary research is not a new one, but approaches to addressing these continue to evolve as society faces more and more complex problems (Jewitt and Görgens, 2000; Lotz-Sisitka et al., 2016).

CHAPTER 02



FIFTY YEARS OF GROUNDWATER RESEARCH

Kevin Pietersen and Sumaya Israel

INTRODUCTION

During the past 50 years of groundwater research funded through the Water Research Commission (WRC), the legal status of groundwater changed from being 'private water' (1956 Water Act) to a public good managed in an integrated manner in terms of the National Water Act, 1998 (Adams et al., 2015). The institutions that have received the most ongoing research funding have been the CSIR and the Institute for Groundwater Studies (IGS) at the University of the Free State from the beginning in 1975 (Braune et al., 2010*). From the 1990s, the UNESCO Chair, established under the direction of Prof Kadar Asmal, in Geohydrology at the University of the Western Cape (UWC) entered as a further major academic player.

The assumption 50 years ago was that the yield of South Africa's groundwater resources would not be sufficient to contribute significantly to the water requirements of the country. At that stage, the potential yield of groundwater was unknown, however, while the estimated groundwater use was $113 \times 10^{6} m^{3}/y$ (RSA, 1970). Research in the 1970s focused on issues of safe yield and delineation of aquifer systems in Groundwater Control Areas, groundwater dependant towns and dolomite aquifers, although the State had little control over private groundwater. This work was mostly done by the then Geological Survey of South Africa. Groundwater personnel in the Geological Survey were transferred to the Department of Water Affairs and Forestry (DWAF) in the 1970s.

Managed aquifer recharge (MAR) studies were also conducted during this time by the CSIR (Murray and Tredoux, 2002*). In the 1980s-90s research on groundwater in fractured rock aquifers began focusing on mapping groundwater resources throughout South Africa and identifying specific groundwater regions or areas of uniform characteristics. In the 1990s, research increasingly focused on matters related to groundwater contamination and quality, as well as groundwater/surface-water interactions and groundwater-dependent ecosystems (GDEs). Groundwater research in the late 1990s/early 2000s broadened its scope, becoming more interdisciplinary and complex, as well as considering basic human needs and human-induced changes in hydrogeologic fluxes and stores. Today, the focus of research is on groundwater governance and unlocking the potential of groundwater resources for conjunctive water use. The overall goal of groundwater research at the WRC has been to promote the optimal and sustainable utilisation of South Africa's groundwater resources through coordinated groundwater research. This chapter describes the various WRC-funded research programmes over the past 50 years that have aimed at meeting this goal.

> ***"The most important constraints or problems in the existing and future water supply of South Africa and South West Africa...underground sources (over-utilisation and insufficient supplementation; and mineralisation) - WRC Annual Report 1973***

Figure 1. The overall goal of groundwater research at the WRC has been to promote the optimal and sustainable utilisation of South Africa's groundwater resources. (Credit: 123RF stock photo).

Groundwater in fractured-rock aquifers

Ninety percent of South Africa's groundwater occurs in secondary-porosity or fractured-rock aquifers, hence WRC-funded research aimed mostly at improving our understanding of these types. These aquifers range in age from earliest Pre-Cambrian to Jurassic (4,000 – 200 million years). Through research various geological provinces could therefore be characterised in terms of groundwater occurrence and potential for exploitation. Techniques and protocols for groundwater exploration were developed; aquifer parameters such as transmissivity and storativity were measured using innovative techniques; and groundwater-management systems were developed.

During the 1980s/1990s a set of national groundwater maps (Vegter, 1995*) was developed as well as a hydrogeological map of Pietersburg (Haupt, 1995*), which culminated in an introductory note on the hydrogeology of groundwater regions (Vegter, 2000*). This work, funded by the WRC, supported the groundwater mapping programme of the then Department of Water Affairs and Forestry (DWAF). Recently, a software tool was developed to automate the geostatistical analysis of available borehole data in a particular groundwater region (North West University, 2020). Parsons (1995*) classified groundwater resources based on the geology, hydrogeology, yield and quality, whereas Parsons and Conrad (1998*) also considered the vulnerability of aquifers, including susceptibility of aquifers to contamination.

The fractured-rock research programme focused on Karoo aquifers, Basement aquifers, Dolomite aquifers and Table Mountain Group (TMG) aquifers, each of which is briefly discussed below.

- **Karoo aquifers** – Approximately 50% of South Africa is underlain by formations of the Karoo Supergroup. The research, conducted under the leadership of Professors Botha, Hodgson, Kirchner and van Tonder at the Institute for Groundwater Studies at the University of Free State, classified the Karoo aquifers as double-porosity aquifers (Botha and Cloot, 2004; Botha et al., 1998*; Kirchner et al., 1991*). The so-called Flow Characteristics Method was developed to estimate the sustainable yield of boreholes in fractured aquifers and this method is now widely applied. In the Western and Eastern Karoo, research by Chevallier et al. (2001*) resulted in a hydro-morpho-tectonic model of Karoo dolerite sill and ring complexes (Figure 4). The hydro-morpho-tectonic model highlighted zones of potential 'open' fracturing which are associated with the emplacement of dolerite sill-and-ring complexes, which have proven to be conducive to the formation of deep-seated fractured aquifers. This work culminated in a handbook on Karoo aquifers (Woodford and Chevallier, 2002*) and a report on research needs for the Eastern Karoo Basin (Murray et al., 2006*). Based on this work a groundwater-planning toolkit was developed for the main Karoo basin for identifying and quantifying groundwater-development options, incorporating the concept of wellfield and aquifer yields (Murray et al., 2012) the project aimed to identify favourable areas of groundwater potential for bulk municipal water supplies, to provide a method to quantify them, and to package the information so that it is assessable for planning purposes. In identifying favourable groundwater areas, the focus turned to developing a detailed transmissivity map of the Main Karoo Basin. In order to present yields in an accessible manner to water-supply planners, the same concept used in surface-water resource assessments and dam or reservoir design were adapted and applied to groundwater. Two methods were developed, namely the Aquifer Assured Yield Model and the Aquifer Firm Yield Model (the latter of which was developed into a software package together with the other products. This work is critical for water supply and used by practising hydrogeologists.

Figure 2. Luc Chevallier prepares for field mapping during the studies on groundwater exploration on dolerite sills in the Karoo, Eastern Cape. (Credit: WRC archives)

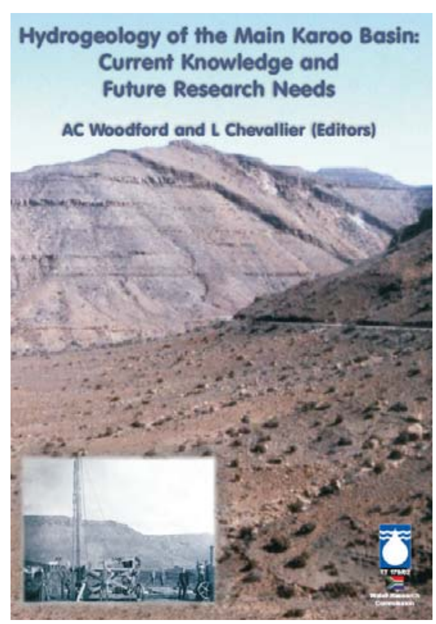


Figure 3. The handbook on Karoo aquifers published in 2002.

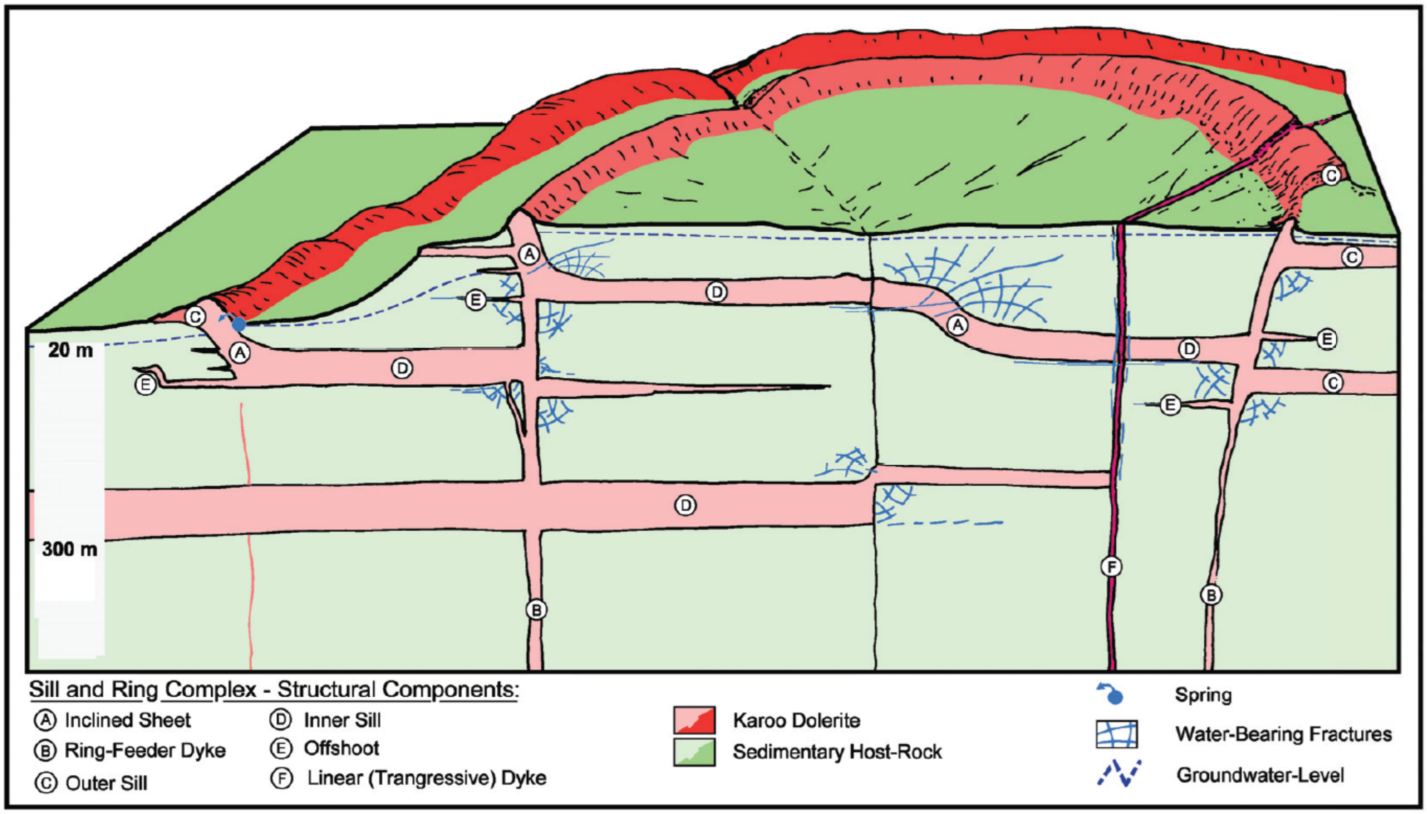


Figure 4. Hydro-morpho-tectonic model of Karoo dolerite sill and ring complexes (Chevallier et al., 2001*) showing the saucer-shape and complexity of the dolerite plumbing system and associated fractured aquifers (Steyl et al., 2012*).

- **Basement-rock aquifers** – Dolomite aquifers occur extensively in the KwaZulu-Natal, Limpopo, Mpumalanga, Northern Cape, and North-West provinces. Knowledge of basement aquifers has been complemented by research carried out by Sami et al (2002a*, 2002b*), Titus et al (2002*), Adams et al (2004*) and Friese et al (2006*) and summarised in a report by Titus et al. (2009*). Later research of crystalline and metamorphic rocks was carried out by Witthűser et al (2011) and Tessema et al (2014*). Sami et al. (2002a*) produced guidelines for groundwater exploration in geologically complex and problematic terrains, including crystalline, metamorphic and igneous rocks.

- **Dolomite aquifers –** Knowledge concerning dolomite aquifers, their occurrence predominately in the Gauteng and North West Provinces, was complemented by research by Connelly et al., (1989*), Bredenkamp et al., (2007*), Bredenkamp and van Rensburg, (2010*) and Wiegmans et al., (2013). Dolomite studies have mostly been carried out by the National Department of Water and Sanitation (DWS) and several geohydrological reports were published. The dolomite aquifers have large transmissivities and storativities, with borehole yields often exceeding 158 x 10^3 m^3/annum (Wiegmans et al., 2013*). Groundwater generally occurs along fault and shear zones associated with intense deformation, resulting in the occurrence of fractures, joints and cavities subsequently enlarged by dissolution processes in the dolomites (Wiegmans et al., 2013*). The Grootfontein Aquifer is part of the important North West dolomite aquifers that supply about 20% of Mahikeng's domestic water needs. Over-abstraction caused the large natural spring draining the aquifer to disappear in 1981, and groundwater levels have since fallen nearly 30 m in the vicinity of the former spring (Cobbing, 2018a). Some of the springs draining the dolomite compartments are large and important for domestic use: for example, the Kuruman Eye is an important water source while the Molopo Eye near Mahikeng and Maloney's Eye near Mogale City are the sources of the Molopo and Magalies Rivers, respectively (Cobbing, 2018b).

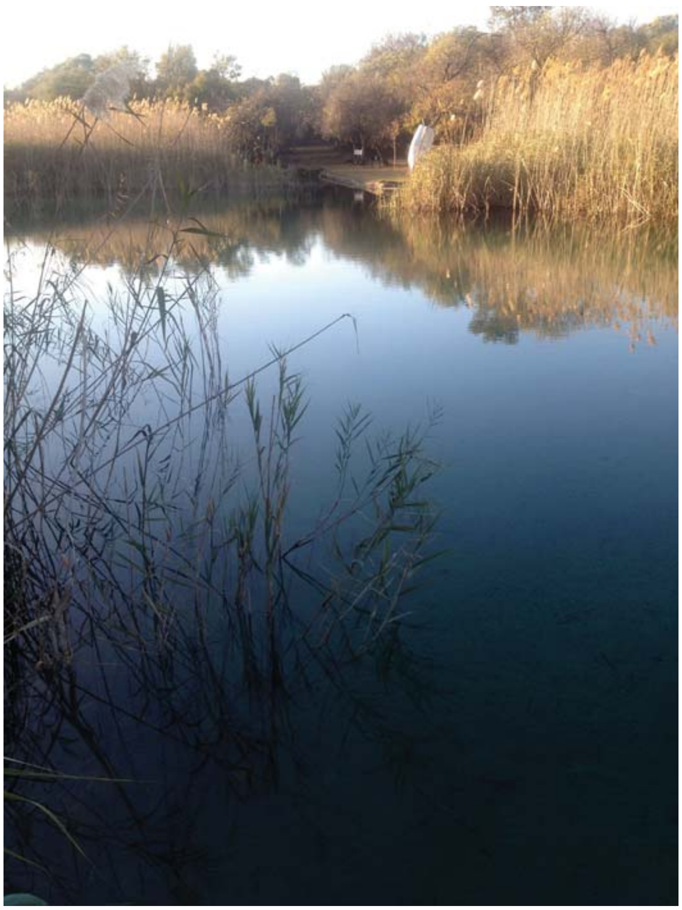


Figure 5. The Molopo Eye near Mahiking is an important source of water for the Molopo River. (Credit: Jude Cobbing)

- **TMG aquifers** – The TMG aquifer comprises a thick sequence of fractured sedimentary rocks. The aquifer can be divided into: the Peninsula aquifer and the Nardouw aquifer, separated by the Cedarberg aquitard (Xu et al., 2009*). The Piekenierskloof aquifer and the overlaying Graafwater aquitard are restricted to the north-western Cape mountains (Xu et al., 2009*). The TMG aquifer is compartmentalised into various hydrogeological units, bounded by large faults, and varying lithologies, and topographies (Xu et al., 2007*, 2009*). Knowledge concerning the TMG aquifers has been complemented by research by Weaver et al. (1999*); Pietersen and Parsons (2002*); Cleaver et al. (2003*); Saayman et al. (2003*); Fortuin et al. (2004*); Umvoto (2005*); Hartnady and Jones (2007*); Xu et al. (2007*, 2009*); Colvin et al. (2009*); Riemann and Blake (2010*); and Lin et al. (2015*).

Figure 6. Cape Fold mountains are also associated with fractured rock aquifers. (Credit: This Photo by Unknown Author is licensed under CC BY-SA)

Deep aquifers

Fourie et al. (2020*) investigated the occurrence of deep aquifers (>300m) in South Africa. The geological formations most likely associated with deep aquifers are as follows.

- **The Limpopo Bel**t – The occurrence of thermal springs suggesting deep groundwater systems (Olivier and Jonker, 2013*)
- The **Witwatersrand Supergroup** Fault zones within the Supergroup play an important role in deep groundwater systems. Where deep gold mines intersect faults there may be large inflows of groundwater.

- The **Transvaal Supergroup** Carbonate rocks of the Chuniespoort and Ghaap Groups represent an important aquifer system here large volumes of water are stored in dissolution cavities
- The **Waterberg and Soutpansberg Groups** Fractures are known to occur at great depth in these rock formations and produce high-yielding boreholes when intersected.
- The **Natal Group** The sandstones and quartzites of the Natal Group have a high quartz content and behave in a brittle manner when deformed, forming local zones of intense fracturing, which enhance recharge and permeability, and create preferential groundwater flow paths. High-yielding boreholes are associated with water-bearing fractures or faults in these formations.
- The **Cape Supergroup** The main groundwater intersections within the TMG occur at depths exceeding 100 m and borehole yields have been found to increase with depth. Deep groundwater circulation has been confirmed within the TMG.
- The **Main Karoo Basin** The occurrence of groundwater in Karoo rocks is mainly associated with horizontal bedding planes and bedding plane fractures. Groundwater has been struck in a borehole near East London at a depth of 3 700 m below ground level. Weathered and fractured zones, which are associated with faulting and folding, occur in the southern Karoo, adjacent to the Cape Supergroup. The shallow anticlines and synclines that are formed due to folding have characteristically open joints and fractures, which are seldom dry when drilled into. The presence of a hot water spring in Aliwal North (Molteno Formation) indicates the presence of a deep circulating groundwater system.
- The **Tshipise Basin** Deep circulating groundwater is evident in the Tshipise Basin from the presence of thermal springs, with maximum water temperatures of 59 to 60 °C (Olivier and Jonker, 2013*). These warm springs are associated with some of the major faults in these basins.

The deep aquifers are generally under confined conditions and associated with positive hydraulic pressures. The groundwater quality generally decreases with depth as salinity increases. Deep dolomitic aquifers may contain groundwater of good quality, however (Fourie et al., 2020*).

Groundwater supply

The lack of basic services, such as water supply and sanitation, was the norm in the underdeveloped rural areas of South Africa. In the 1990s, groundwater was identified as a strategic resource to meet basic human needs for potable water, especially in semi-arid and arid regions. The overall aim was to optimise groundwater utilisation for all communities through an integrated management approach. In the early 2000s the WRC funded the development of guidelines for monitoring at community level, as well as guiding the local water committee or water provider in basic water management practices. This was done by assisting in the design and implementation of an affordable, community-driven groundwater monitoring and information system from which a management scheme could be developed. Emphasis was on self-management by the community to ensure sustainable water supply over the long term, and to create ownership of the resource (Meyer, 2002*).

Another WRC-driven study developed groundwater operating rules for rural water supply through the development of groundwater storage-reliability analysis curves (Odiyo and Makungo, 2016*). Work has also been done on understanding the barriers to better use groundwater for local water supply in South Africa. This work supported the contention that rolling out better and more reliable groundwater supplies is not primarily a technical or hydrogeological issue as many other factors need to be considered. The main reasons for lack of access are linked to inadequate installation and operation and maintenance of water supply systems, which in turn depend on a variety of subsidiary factors and/or institutions (Cobbing et al., 2015). Work was also done to improve the reliability of spring-water supply to more accurately assess the flow and flow variations from small springs by used for community water supply at remote sites (Pearson et al., 2003*).

Based on literature review and case studies, a Groundwater Management Framework was designed for use at local levels of responsibilities such as Water Service Authorities, Water Service Providers, and Water Users Associations (Riemann et al., 2012*).

The framework includes a detailed description of the different functions and the relevant responsibilities, the required skills, the optimal position within the municipal structure and required communication lines (Riemann et al., 2012*).

Urban groundwater

Rapid urbanisation and economic development in South Africa are increasing the pressure on natural resources. This is particularly true of groundwater, which is prone to pollution because of indiscriminate disposal of harmful substances and inadequate protection measures. To address groundwater vulnerability to pollution, a programme on Groundwater Quality and Protection was formulated by the WRC, the overall aims being the assessment of the occurrence, degree and potential of groundwater contamination and the development of suitable techniques for groundwater protection.

Parsons and Tredoux (1993*) developed a strategy to monitor groundwater quality on a national scale concluding that the key factors to the successful establishment of a national groundwater quality monitoring network are obtaining adequate financial resources, appointing a Review Committee to guide the process and appointing a network manager to administer the process. Initiating the national network using a pilot program is considered fundamental to the attainment of a national groundwater quality monitoring network (Parsons and Tredoux, 1993*). Based on all the reliable waste disposal site data currently available in South Africa and the work performed during the research programme, the Waste-Aquifer Separation Principle (WASP) was put forward to provide an accurate and quantified assessment of a site's suitability for waste disposal, based on geohydrological criteria (Parsons and Jolly, 1994a*). A WASP manual was produced to support implementation of the research. (Parsons and Jolly, 1994b*)

As a result of the report by Wright (1999*) on the impacts of informal settlements on groundwater, the WRC identified the need to ascertain whether groundwater contamination from growing urban areas and informal settlements was a national problem or not. It was concluded that the most significant pollutants at the time were nutrients (nitrogen and phosphorus species), pathogenic micro-organisms and biodegradable organics. At that time, other pollutants such as heavy metals and refractory organics, commonly linked to industrial activities, had not yet been found in groundwater. Wright (1999*) recommended that future research should focus on vulnerability mapping and assessment of groundwater pollution in these urban centres.

Sililo et al. (2001*) were tasked with developing a research strategy relating to protocols for assessing the impacts of groundwater pollution and considering means of groundwater protection. The main recommendations of this strategy lead to the development of research around identifying and prioritising urban groundwater contaminants (Usher et al. 2004*) and new approaches in aquifer vulnerability assessment (Saayman et al. 2007*). Usher et al. (2004*) developed a tiered risk-based prioritisation tool with which both sources and contaminants could be rated, and an excel-based data information system in which contaminants, associated sources and contaminant properties could be stored. The identified contaminants in the urban setting and groundwater in general were not necessarily included in routine monitoring programmes, so the magnitude of their impacts was not known. The team was able to develop an urban-risk-assessment software package that used a tiered approach, including identification of sources and prioritisation of contaminants.

Their work was followed by the ***Assessment of vulnerability for South African aquifers*** (Saayman et al., 2007*), which took into consideration the soil and saturated zones in the assessment of aquifer vulnerability. The team assessed vulnerability in primary coastal and dual-porosity systems in South Africa, using a GIS-based approach, which allows the use of various layers in map format that planners can easily relate to. This study was an in-depth scientific approach that took the unsaturated zone and flow and transport in the saturated zone into account. It also linked the findings to decision making.

More recent studies are related to urban groundwater considering water-sensitive urban design (WSUD) (Armitage et. al., 2014*). Regarding groundwater, WSUD addresses groundwater management, including artificial recharge and use of groundwater. Armitage et. al. (2014*) note that urban infrastructure, whether related to stormwater, wastewater or water supply, is linked to groundwater and has impacts on the quantity and quality of groundwater. WSUD therefore requires a sound understanding of the relationship between groundwater and urban infrastructure to ensure that appropriate water quality and quantity are achieved and maintained. Furthermore, groundwater is discussed in terms of its interactions with infrastructure, as part of ecosystem services in the urban setting where groundwater-dependent ecosystems may exist, and as a location for storage of additional water resources in the form of managed aquifer recharge.

Seyler et. al. (2019*) considered urban groundwater development and management, addressing the status quo of urban groundwater development and management in South Africa and comparing it to best practices. Investigations showed that five metropolitan municipalities – the City of Tshwane, Nelson Mandela Bay municipality, the City of Cape Town, Buffalo City (domestic supply to coastal villages) and Mangaung (domestic supply to rural Thaba Nchu) – already used groundwater, although it contributes only a small percentage of the total water supply in these metropolitan municipalities.

Figure 7. Few people realise the importance of groundwater in the supply of water to cities, such as Pretoria. (Credit: Lani van Vuuren)

Groundwater protection

Groundwater protection has been included in many WRC-funded projects, including those considering vulnerability to groundwater pollution (Wright 1995*; Sililo 2001*; Usher et. al. 2004*, Saayman et al. 2009* and Seyler et. al., 2019*). The vulnerability of an aquifer to such pollution is directly linked to hydraulic characteristics of the overlying vadose zone and to a significant degree is determined by the characteristics of contaminant attenuation.(Sililo et al., 2001*). Groundwater protection is based on three pillars, namely, the legislative framework, implementation and management, and understanding of complex systems (Riemann et al. 2017) – in other words, government, science and society. Dippenaar et al. (2010*, 2014*, 2019*) have further advanced our understanding of vadose-zone hydrology. This knowledge informs the properties dictating the hydraulic characteristics of the hydrostratigraphy of South Africa (Dippenaar et al., 2019*).

The National Water Act (1998) alludes to the protection of groundwater, in particular by means of proactive measures also known as resource-directed measures. This requires classification of water resources, determining the Reserve and setting Resource Quality Objectives. This approach makes provision for determining the level of protection that should be afforded to a water resource to maintain a certain level of ecosystem integrity. Resource-directed measures for groundwater were first addressed by Xu et. al. (2000), Parsons and McKay (2000), Xu et. al. (2003), Parsons and Wentzel (2007) and Dennis et. al. (2013). Concurrent work focused on implementation and identification of groundwater protection zones, while Dennis et. al. (2002*) considered a risk-based approach to groundwater protection, taking into consideration sustainability in terms of groundwater use and contamination. Dennis et. al. (2002*) and Usher et al (2004*) using a fuzzy logic approach and taking contaminant properties into account, focused on the urban groundwater environment. Nel (2013*) focuses on establishing groundwater protection zones in fractured rock aquifer settings and considers all the necessary data types and information required to delineate groundwater protection zones.

The WRC has funded studies dealing with the impact on groundwater of land-use activities, such as agriculture, mining and unconventional extraction of gas. Nitrate was the most common agricultural contaminant evident in groundwater sampled (Conrad and Colvin, 2000*; Conrad et al., 1999*). Accumulation of salts in groundwater is also due to irrigation in the Vaalharts Irrigation Scheme and the Great Fish and Sundays rivers (Conrad et al., 1999*; Ellington et al., 2004*; Verwey et al., 2011*).

Mining is one of the oldest industries in South Africa. Although mines are big contributors to our economy, they are often large water users, and in many cases also some of the biggest polluters of water resources. In this regard, the largest issue experienced with respect to mining is acid mine drainage, which is highly acidic and with high concentrations of iron and sulphate. This toxic groundwater can reach other parts of the environment when mines decant or even during transfer of mine wastes to tailings dams. It can result in precipitation of metals into the environment, while its acidity means that it is likely to mobilise metals that would otherwise remain attached to soil or rocks.

A study by Heath et al. (2004*) considered the impacts of small-scale mining on water resources. The authors concluded that many of the effects of small-scale mining on the aquatic environment might well be insignificant if occurring in isolation, but when they occur simultaneously, their significance may increase by orders of magnitude. The overriding principle is that the greater the number of small-scale mines in an area, the greater the cumulative impacts on the aquatic environment.

South Africa may have the potential to develop a domestic supply of natural gas from shale gas resources found in the main Karoo Basin. Murray et al. (2015*) assessed the geochemistry and deeper circulation of groundwater in the Karoo basin, prior to any hydrofracturing taking place, as baseline information because understanding of the system is important, if it is to be properly managed. Esterhuyse et al., (2014*) produced an interactive vulnerability map and monitoring framework to assess the potential environmental impact of unconventional oil and gas extraction by means of hydraulic fracturing. Concurrent work by Pietersen et al. (2016) deemed it critical to develop and implement effective groundwater governance arrangements. They analysed existing policies and plans to determine whether critical gaps or barriers exist that could potentially lead to impacts on groundwater systems. Pietersen et al. (2020) provided a prospective analysis of hydrogeological risk pathways and vulnerability attributes in advance of anticipated shale gas operations in the Karoo Basin of South Africa. The 'hazard-pathways-receptors' approach was applied to define the hydrogeologic system in the context of potential sources of water resource contamination. This case study focuses on two critical hydrogeological risk pathways: regional groundwater flow and discrete structural features. The knowledge gained through WRC research support has made it possible to develop pro-active safeguards.

Figure 8. A typical active hydraulic fracturing site. Several WRC-funded studies have focused on the sustainable management and potential impact of this economic activity on South Africa's groundwater sources. (Credit: WRC archives)

Groundwater and ecology

Groundwater-dependent ecosystems (GDEs) occur throughout the South African landscape in areas where aquifer flows and discharges influence ecological patterns and processes (Colvin et al. 2007*). Colvin et al. (2003*) developed a preliminary nationwide map showing the probability of occurrence of terrestrial GDEs based on groundwater levels and the duration of adequate moisture during the growing season. The research provided a summary of the various techniques available to assess groundwater use by plants. Each was assessed using case studies. Examples of known South African GDEs and species include (Colvin et al., 2007*):

- in-aquifer ecosystems in the dolomites (Northwest Province)
- springs and seeps in the TMG sandstone (Western Cape)
- terrestrial keystone species such as ***Vachellia erioloba*** (camelthorn, previously ***Acacia erioloba***) in the Kalahari
- lakes and punctuated estuaries on the shallow sand aquifers of the east coast in KwaZulu-Natal
- riparian zones in the seasonal alluvial systems of the Limpopo River seeps on Karoo dolerite sills

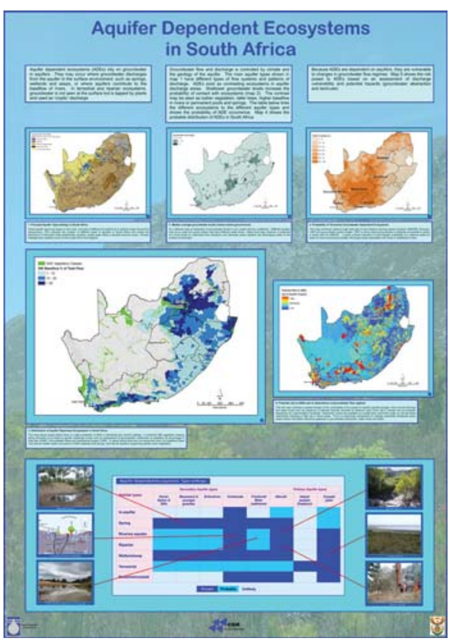


Figure 9. The groundwater-dependent ecosystem poster developed in 2007.

The WRC has supported research examining the impact of groundwater abstraction on riparian vegetation, terrestrial vegetation, springs and surface water. In the early 2000s detailed studies were conducted on the effect of large-scale groundwater abstraction from the Klein Karoo Rural Water Supply Scheme (Cleaver et al., 2003*), concluding that the scheme has affected low-flow discharges of the Vermaaks River. This work was followed by a study focusing on the environmental impacts of large-scale groundwater development in the TMG Aquifer System (Colvin et al., 2009*). The study found a continuum of elements of ecosystems linked to water availability via soil moisture, perched aquifer, aquitard / aquifer contact and regional aquifer springs. Invasive alien plants have occupied large parts of South Africa. Mesquite, the arid-adapted trees Prosopis spp, are major invaders in the arid and semi-arid parts of the country. Dzikiti et al., (2018*) found that Prosopis consumes at least 4 200 m^3 of groundwater per hectare per year, compared to only 420 m^3/ha/yr for ***V. karroo***, which is indigenous, indicating that clearing Prosopis is an effective strategy for increasing availability of groundwater, which is critical in groundwater dependent communities.

Managed aquifer recharge

During the 1970s, the potential of the Cape Flats Aquifer for MAR, i.e., the storage and abstraction of groundwater or reclaimed treated domestic wastewater was evaluated (Tredoux et. al., 1980). Field testing showed that MAR could be successfully implemented but that failure occurred due to the high turbidity of the wastewater causing clogging in the test basins (Tredoux et. al., 1980). The MAR technology was adopted and adapted for the town of Atlantis shortly afterwards. The Atlantis managed aquifer-recharge scheme is the longest successfully running recharge scheme in South Africa (Bugan et al., 2016). An initial assessment and feasibility study of artificial recharge schemes in Southern Africa identified the need for testing the concept in fractured rock aquifers (Murray and Tredoux, 2002*). Three of the pilot sites, Windhoek, Calvinia, and Karkams (a small Namaqualand village), are underlain by secondary aquifers and high-quality water was needed for borehole injection. At the fourth site, in Polokwane, alluvium overlies fractured gneisses allowing the infiltration of treated municipal wastewater from the riverbed into the aquifer. The scale of water supply varied from Windhoek, requiring more than fifteen million m^3/y to Karkams, needing only a few thousand m^3/y.

In their report of 2002*, Murray and Tredoux describe the testing of water resource development in fractured aquifers. By then, full-scale artificial recharge schemes were already in place in Atlantis and the Omaruru delta in Namibia, demonstrating that the techniques were effective in recharging such aquifers. They set out to pilot artificial recharge in South African secondary or fractured rock aquifers and to demonstrate its potential to hydrogeologists and water-resource planners. This project successfully demonstrated the feasibility and potential of artificial recharge to secondary aquifer systems and indeed the City of Windhoek soon started a full-scale managed artificial recharge scheme.

The main recommendations of the study were that artificial recharge be applied in areas where groundwater is over-abstracted (higher volumes compared to recharge); in areas with surplus seasonal surface water where abstraction and recharge are in balance and more water is required in the region; in areas where groundwater is saline or non-potable; in areas where a buffer zone may be required between good and poor-quality water; and in primary aquifers that are suitable for secondary treated wastewater. They also recommended the consideration of conjunctive use of groundwater and surface water, and the potential use of strategic aquifers such as the TMG aquifers to reduce loss to evaporation from large open surface waters (Murray and Tredoux, 2002*).

The successful testing and implementation by Murray and Tredoux (2002*) led to follow-up studies considering feasibility, pilot testing and implementation of managed aquifer recharge schemes in various parts of the country. During 2003*, Murray and Tredoux compiled a document called *Water-wise management for towns and cities* and in 2007 DWS, with support from the WRC, developed an artificial recharge strategy with the vision "To use natural sub-surface storage as part of Integrated Water Resource Management wherever technologically, economically, environmentally and socially feasible". In 2011, *Water banking - A practical guide to using artificial groundwater recharge* was published by DWS (Murray, 2011).

Figure 10. The simple sand filter in the bed of the river, which flows through a valley carved from granite at the Karkams artificial recharge scheme. (Credit: Water Wheel archives)

MAR has been incorporated into urban water planning by being viewed as an option for improving sustainability and re-use of water resources in urban areas. WSUD and sustainable drainage systems incorporate elements of artificial recharge for urban parts of the country. The occurrence of drought conditions has increased the number of municipalities that have considered MAR and conjunctive use of water sources as options for the future. MAR is also currently being included under 'nature-based solutions'. Ongoing research is evaluating the use of MAR in farming communities with the aim of securing sufficient water to ensure sustainable crop yields.

Groundwater and climate change

In the early 2000s the adaptive capacity of small towns and communities to climate variability, specifically drought, was studied by Mukheibir and Sparks (2005*). To assess the potential effects of climate change on Karoo aquifers, a regional screening tool, known as the DART index, was developed. The DART index is used to identify areas that may experience changes in their groundwater resources as a result of climate change (Dennis and Dennis, 2012*). For a more detailed discussion of the WRC's contribution to studies on climate change, see chapter 12.

Groundwater economics

Aquifers are natural assets forming part of the ecological infrastructure. Groundwater provides a range of services, but the benefits provided by these services are often not fully appreciated or factored into decisions about groundwater management and use (Bann and Wood, 2012). Limited work has been done on valuing groundwater. The only WRC-funded research related to valuing groundwater was done by Pearce et al. (2014*). Using the Millennium Ecosystem Assessment Framework (MEAF) in combination with a method known as a Comparative Risk Assessment (CRA), the study investigated the ecosystem services of the groundwater resource through expert analysis of three case studies. Aquifers are viewed primarily as a source of groundwater, with the provision of water being regarded as the sole benefit derived from aquifers. The prevailing approach to groundwater management in South Africa is almost entirely centred on the abstraction of water resources for economic consumption and does not account for the broader range of ecosystem services provided by aquifer systems.

Groundwater governance, law, and regulation

There is the recognition that lack of technical knowledge of an aquifer cannot be blamed for poor management of groundwater resources. A more holistic view of South Africa's groundwater as a national resource is required, taking into account the wider management, funding, legal, policy, and operational context as well as the hydrogeological realities (Cobbing, 2018a).

The WRC has supported research on groundwater governance in South Africa at both national and local levels. At the local level, groundwater governance was studied for four highly productive aquifer systems, demonstrating various degrees of implementation of groundwater governance: (i) Botleng Dolomite Aquifer (Delmas area); (ii) Gauteng Dolomites (Steenkoppies and Bapsfontein compartments); (iii) Houdenbrak Basement Aquifer (Mogwadi (Dendron)-Vivo area); and (iv) Dinokana-Lobatse Transboundary Dolomite Aquifer (Pietersen et al., 2011*). The finding, amongst others, was that local governance of groundwater is weak to non-existent. The WRC, therefore, supported research to address weaknesses in governance by identifying and prioritising key interventions that can improve local groundwater governance in South Africa (Seward, 2015). The research made the following key recommendations for interventions (Seward, 2015).

- The first is a 'one-step-at-a-time' approach, whereby attention is given to the implementation of one design principle at a time. The principle selected should be the one that would be most beneficial to the local stakeholders and the most feasible for the external agency to assist.
- Secondly, initiatives to improve local groundwater governance should take cognisance of, and be guided by, the need to improve social capital at all levels.
- Thirdly, in the case of South Africa, initiatives to improve local groundwater governance should be driven by an agency or organisation outside of DWS.

The lack of political and social capital is preventing provision of groundwater services in local municipalities. In developing the social capital, the WRC has developed training manuals for groundwater resource management and groundwater governance for municipalities in South Africa (Kotzé et al., 2019*).

Groundwater innovations and tools

Groundwater capture

The WRC has funded several studies aimed at understanding groundwater recharge and discharge. These include the development of techniques for estimating groundwater recharge. Recharge is related to the amount of rainfall and the position of the aquifers within the landscape, which is, in turn, related to altitude and topography. Recharge mainly occurs when rainfall is above normal. Rainfall in semi-arid regions is episodic in nature, where most of the annual rainfall can occur within a short period of time with a concomitant increase in recharge if favourable conditions exist, as opposed to distributing the rainfall over an entire year. The use of mean annual recharge rates can be misleading, as the simulated period only includes years of above-average rainfall and not the long-term cyclicity of rainfall (Adams et al., 2004*). Recharge occurs as primary recharge in the mountainous areas where direct infiltration is more likely. Indirect recharge involves the infiltration of surface runoff and discharges from springs and adjacent aquifers, dominating in most of the areas. However, there has been a move away from a water balance approach to an capture approach (Seyler et al., 2016*). This resulted in a decision framework representing the recommended approach to establish operating rules. The operating rule grades, and associated sustainability indicators, provide a mechanism to implement the adaptive management cycles necessary to update maintainable aquifer yields, and in turn, operating rules (Seyler et al., 2016*).

Geophysics

Some years ago the WRC supported studies using high-resolution geophysical techniques, such as radiowave and seismic tomography to assess the usefulness of these techniques in characterising the nature of aquifers on a micro-scale (over ranges of metres, with resolutions of tens of centimetres) compared to the more traditional geohydrological techniques available (Meyer et al., 1998*). The results of the radiowave and seismic tomography experiments have been very promising, and it was recommended that these techniques be employed as the prime high-resolution geophysical tool to obtain detailed information on rock and aquifer structure when the demands on the project are such that detailed information is required (Meyer et al., 1998*). Since that time, however, there has been only limited funding for geophysics research.

Numerical models, databases and analytical software

Pumping tests are critical for determining the hydraulic behaviour of a borehole, the reservoir and the reservoir boundaries. Van Tonder et al. (2002*) analysed pumping tests in fractured rock systems and developed a manual for conducting and evaluating pumping tests in these aquifers. During the 1990s the development and application of groundwater optimisation models for the control of groundwater hydraulics and water quality, and the inverse problem of parameter estimation, were developed, resulting in the production of the groundwater management package, AQUAMOD (van Tonder et al. 1999*). The advent of commercial geohydrological software packages has made it obsolete to pursue software development. The development of the Windows Interpretation System for the Hydrogeologist (WISH) software followed a similar route.

Big-data analytics

The WRC managed a series of projects focusing on Big Data Analytics (BDA). Advances in remote sensing missions, atmospheric and land surface models, social media, and other internet-related platforms provide new and additional sources of data for groundwater. BDA covers a comprehensive package of advanced analytical, statistical, mathematical and graphic methods that can be used to transform the data into useful information (Russom, 2011). The research projects that have been implemented are the following.

- *Imagining solutions for extracting further value from existing datasets on surface and groundwater resources in Southern Africa* (Nuapia et al., 2020*). The approach involved a survey of the perceptions of stakeholders (DWS; Rand Water, East Rand Water Care Company; academics in water and environmental research; and officials from the Ngaka Modiri Molema Municipality and the Ramotshere Moiloa Local Municipality) to obtain water data and other relevant information that was used to gauge their perceptions on big data and citizen science. This included conducting big data analytics on the data; text mining on citizen science; and building citizen science into the big data context. The patterns and trends in the clusters generated from the data analytics showed a general agreement with some of the observations from citizen science and confirmatory surveys. The majority of the water was clustered as of acceptable quality, which was corroborated by the citizen science in both rural and urban areas. It was demonstrated that citizen science is important to consider when compiling datasets and conducting big-data analytics. The good model metrics show that it can be used with confidence for unseen data or new cases.

- *Localising transboundary data sets in Southern Africa: a case study approach* (Gaffoor et al., 2020*). Two case study areas were chosen to explore the applications of Big Data Analytics to groundwater management: The Zeerust/Lobatse/Ramotswa Dolomite aquifers of Botswana and South Africa, and the Shire Valley Alluvial Transboundary Aquifer (TBA) in Malawi and Mozambique. The status quo of the TBAs was discussed within the context of undesirable results, based on a set of groundwater management scenarios adapted from the California Department of Water Resources. From this, the scenario of chronic lowering of groundwater levels was investigated using Big Data analytics. A Gradient Boosting Decision Tree (GBDT) was used to develop a generalised machine learning model to predict 30-day groundwater level changes at ~5 x 5 km resolution across the study areas.
- *Consolidation of data and application of big data tools to enhance national and transboundary data sets in Southern Africa that support decision-making for security of water resources* (Gemmel et al., 2020*). The project developed software tools to automate the collation and quality control of data from existing online databases into a format suitable for a primary repository, the existing SADC-Groundwater Information Portal (GIP). This included protocols on designing a monitoring network, procedures for recording data (including metadata, logical and outlier checks), and a standard procedure for handling erroneous or dubious data.
- *Machine-learning models for groundwater availability, incorporating a framework for a sustainable groundwater strategy* (Seyler et al., 2020*). The research showed that machine-learning models have application in aspects such as assessment of the cause of patterns in datasets, predicting the short-term impact of climate variability, and filling data gaps. Their applicability to predicting the impacts of abstraction to inform thresholds of acceptable impact is limited, however.

In-situ treatment methods

During 2004*, Tredoux and Clarke investigated remediation technologies for nitrate removal, while Johnson et al. (2005*) examined the possibility of using permeable reactive barriers (PRBs) in treating acid mine-water. Johnson et al. (2005*) assessed the applicability of PRBs to the South African setting and tested the methods in the laboratory, using zero-valent iron as a barrier material to remove uranium from dolomitic water of high pH.

The distribution of nitrate levels close to sole-source towns emphasised the urgent need for remediation technologies to be tested. Israel (2007*) evaluated bench- and pilot-scale denitrification processes, showing that denitrification in the subsurface is likely to occur as long as there is sufficient substrate (organic carbon source) and the system is not carbon limited. Denitrification was successfully demonstrated in the field in the Cape Flats Aquifer and monitored over a three-year period to predict a potential barrier lifespan (of the carbon source) of approximately eight years (Israel, 2012*). Interestingly, a low-technology approach of woodchips for denitrification was found to be appropriate for rural application, where low maintenance and rigorous methods would be best suited (Israel 2012*).

Over the past few decades, borehole clogging, which reduces borehole yield considerably, has often been reported. Especially in the Klein Karoo Water Supply Scheme (Cleaver et al., 2003*) and the Atlantis Aquifer (Murray and Tredoux, 1998), where water from the boreholes is used for drinking. Several studies funded by the WRC examined the occurrence and reasons of clogging, including links to geological and physico-chemical conditions (Robey, 2014).

Capacity-building in the groundwater field

The WRC investment into groundwater research in South Africa has been strategic and ongoing for 50 years to date. This investment has, in all probability, been the most significant contribution to the building of capacity for the sustainable utilization and management of groundwater resources in

South Africa (Braune, 2010*). The WRC was and is instrumental in developing the strong research and teaching centres in groundwater hydrology in South Africa (e.g. Institute for Groundwater Studies at the University of the Free State and the groundwater programme within the Earth Science Department at the University of the Western Cape).

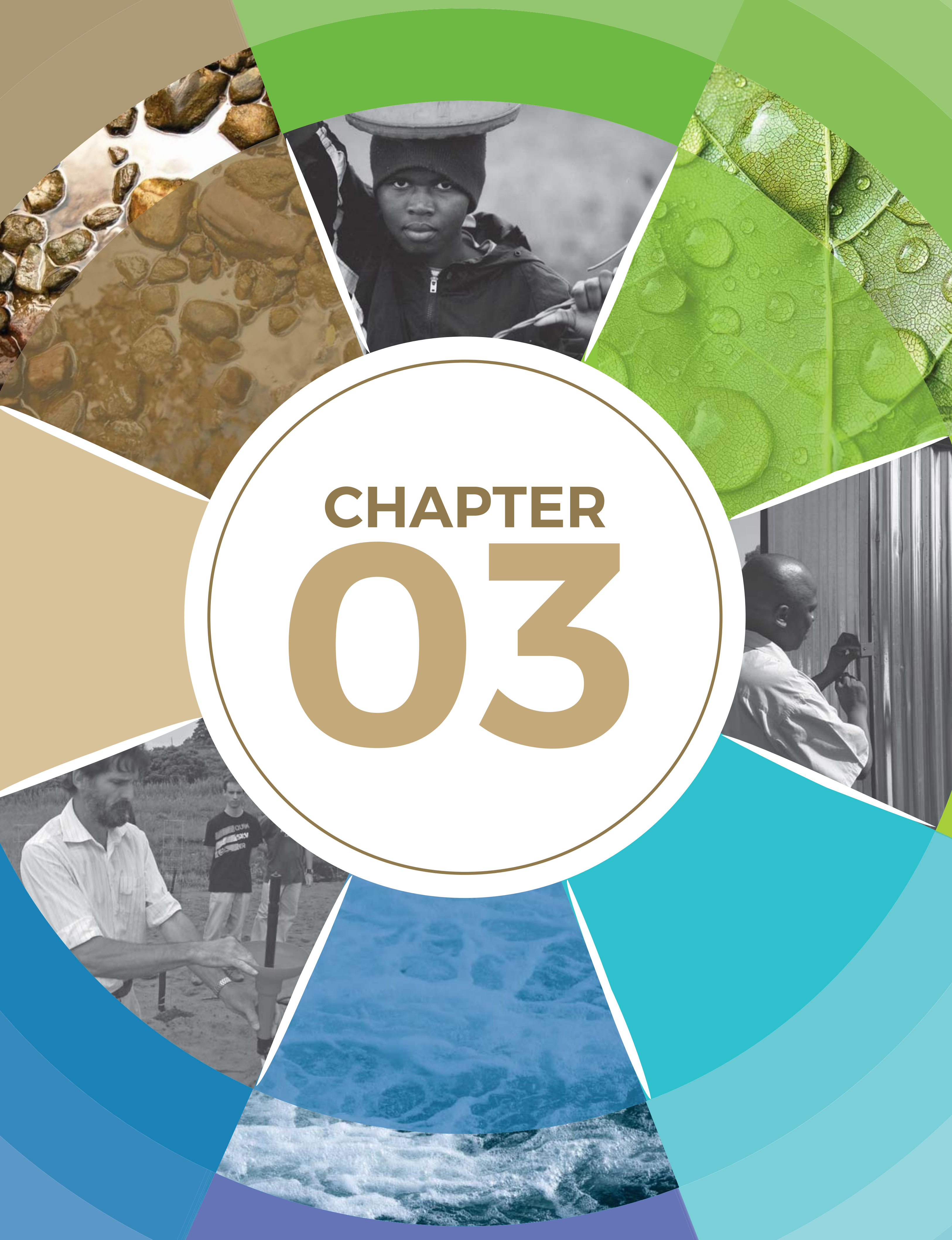
The WRC has also supported students from several other universities (Fort Hare, Venda, Pretoria, KwaZulu-Natal and Witwatersrand), science councils, NGOs and consulting firms (Braune 2010*). The WRC has supported the Framework Programme for Research, Education and Training in the Water Sector (FETWATER). FETWater Phase I successfully established three networks, including the Groundwater Network. FETWater Phase II continued to support existing networks and the creation of new networks that contributed to integrated water resource management. However, the lack of linkage to sector skills planning and delivery systems for professional and career development i.e., the over-emphasis of academic orientation of the networks was observed as a challenge in the water sector. In FETWater III the capacity building paradigm was changed to follow an occupationally directed approach.

Gaps in groundwater research and future perspectives

The WRC has made significant advances in groundwater research, contributing to tools and techniques that advance groundwater role in the water supply mix. The current situation is that urban groundwater is heavily under-utilised. Further, human capacity and the operation and maintenance of groundwater infrastructure at the local level are responsible for supply issues, rather than groundwater availability. The future holds an accelerating demand for water, including marginal water resources to address poverty, unemployment and inequalities, which remain entrenched. The focus will need to be on groundwater governance at local level, with pragmatic solutions that tie into the capacity to implement at resource-use at local level. Some of the themes for future research include:

- The connectedness of groundwater to various parts of the Earth system across different scales.
- Conjunctive use of water resources, including alternative water resources.
- Scale aspects of groundwater flow and transport systems.
- Critical zone sciences – where much of the Earth life-sustaining activities such as food production and regulation of water quality take place.
- Upscaling / downscaling – new techniques and approaches.
- Local scale, pore scale, and discrete scale processes
- Polycentric groundwater governance systems – interaction between actors at different levels of governance
- Improving shared sustainable use of groundwater resources that cross two or more jurisdictional borders.

Figure 11. Recent droughts in South Africa have underlined the importance of groundwater as a resource. (Credit: 123RF stock photo)



CHAPTER 03

WATER AND SANITATION SERVICES – PROVIDING A BETTER LIFE FOR ALL

Jay Bhagwan, Nonhlanhla Kalebaila, Errol Malijani, Shawn Moorgas, Sudhir Pillay, Jody Reizenberg and John Zvimba

INTRODUCTION

South Africa has strong research and training capabilities in the fields of water supply and sanitation (Ashton et al., 2012*). The main purpose of the research that is funded by the Water Research Commission (WRC) is to ensure that water supplies are adequate to support economic growth in South Africa (Tempelhoff & Stopforth, 2014*). Consequently, investments in water supply and sanitation services are mainly in urban areas, and are highly centralised, and regulated.

In the second half of the twentieth century, South African excellence in water supply planning and development was recognised internationally (King & Pienaar, 2011*). Water supply projects that gained global attention included the Vaal Dam, which was commissioned in 1937 and the Orange River Scheme, as well as water reuse and reclamation research that culminated in the commissioning in 1968 of the potable water reclamation plant in Namibia, the first potable water reuse plant in the world (Tempelhoff & Stopforth, 2014*).

The continuing increase in the demand for water, and the increase in the discharge of treated and untreated wastewater into rivers and wetlands, triggered questions concerning the sustainability of South Africa's freshwater resources. This led to the development of new ways to efficiently manage the country's water resources in terms of both quantity and quality.

In the aftermath of the severe drought of the 1960s, the Water Research Act (No. 34 of 1971) for the establishment the WRC was promulgated. At that time the major issues identified for investigation by the WRC included water resources assessment, means of augmenting water supplies by increasing water use efficiency, how to address water pollution, governance issues related to water resources management and water services provision, as well as research and capacity building in the water sector (Water Research Commission, 1974*).

Since its establishment in 1971, research funded by the WRC has been pivotal in providing South Africa's policymakers, water users and stakeholders with sustainable solutions to long-standing issues of water supply, water and wastewater treatment, and water quality. The WRC's 2014 report entitled ***South Africa's 20-year journey in water and sanitation research*** describes South Africa's history of research into issues concerning water and sanitation.

Figure 1. The 2014 publication which describes South Africa's history of research into issues concerning water and sanitation.

The WRC's strategic research agenda currently addresses three Key Strategic Areas (KSAs): Water Use, Wastewater Resources and Sanitation Futures. These KSAs support research aimed at improving the provision of reliable and affordable supplies of water of adequate quality and quantity for domestic and economic activities (industrial, commercial and mining). Also linked to water supply is the all-important aspect of the protection of human health, and for this reason the WRC also focuses on the development of innovative technologies, processes and procedures that address aspects related to bulk supply, treatment technologies for potable water and wastewater, and distribution and quality of water for potable use.

At the time that the WRC was established, it embarked on an ambitious research programme to expedite the development of the technology of water reclamation for potable supply (recycling), and to study the health effects of recycled water, including concerns following the outbreaks of cholera in 2000 (Hemson et al., 2004). This led to the protection of human health becoming a key focus of the WRC, with emphasis on the quality of both drinking water and wastewater. Post South Africa's 1994 elections, the WRC's focus expanded to include issues of water services and sanitation. The emphasis on these key elements was aimed at providing long-term water security in South Africa.

WATER USE

Throughout the 50 years of the WRC's existence, there has been a constant focus on research aimed at supporting government initiatives in fast-tracking water services. One of the many water-supply challenges that South Africa has fast-tracked since 1994 is the provision of adequate and safe water services for previously disadvantaged communities.

The WRC projects that were commissioned in the early 1990s mainly focused on assessing the status quo, and on evaluating the technological performances and costs of existing water-supply systems, with a view to developing new policies and water supply options to meet the backlog in the provision of water services to previously disadvantaged communities. Examples of case studies undertaken in the early 1990s are the studies of water-supply systems in densely populated residential and rural areas, as well as studies of bulk water supplies in metropolitan cities (Palmer Development Group,1994*; Martin & Pansegrouw, 1995*).

Findings from these and other studies paved the way for the promulgation of policies and legislative frameworks for water services provision in South Africa. The 1996 Constitution, the Water Services Act (Act No. 108 of 1997) and the National Water Act (Act No. 36 of 1998) stipulate the responsibilities of the various governmental water service institutions (mainly water boards and municipalities) for water supply, treatment and quality management in order to ensure that all South Africans have equitable access to safe water supplies.

Addressing the water services backlog

Since 1994 the new democratic government of South Africa has concentrated on the delivery of water and sanitation infrastructure to reduce the backlog in the provision of basic water services for all communities in South Africa. The Water Supply and Sanitation White Paper of 1994 and the Water Services Act of 1997 provided the policy and legislation needed to guide and pioneer this mandate during the first ten years of democracy. The Local Government Act of 1998 and the Municipal Systems Act of 2000 provided the legislative framework for local government to take full responsibility for water services delivery, as mandated by the Constitution. The WRC was at the forefront of providing support for this transformation of the legislation for water services and in providing the strategic framework (PDG, 2009*) for setting out a comprehensive approach towards improving water services in South Africa, as mandated by the Constitution. As discussed below, the WRC has focused efforts in a number of ways to achieve these policy goals.

Eradicating the backlog in the provision of potable water and sanitation

Research under this theme has been aimed at developing new approaches to eliminating the backlog in the provision of potable water supply and sanitation so as to enable poor communities to make productive use of domestic water supplies in order to facilitate their escape from poverty. The national government planned to clear the water services backlog by:

- Providing basic water supply infrastructure for all by the year 2008
- Providing access to basic sanitation services for all by 2010
- Implementing the Free Basic Water policy in all municipalities by 2005

Figure 2. A significant focus for the South African government since 1994 has been the elimination of the backlog in basic water services. (Credit: WRC archives)

In order to reduce bias in the provision of adequate water supplies the WRC focused its efforts on research to improve the treatment of potable water and wastewater, with a substantial portion of the budget for such research being made available to disadvantaged institutions. An assessment of the impact of the water-related studies funded by WRC (Conningarth Economists, 2004*) indicates that, between the year 1999 and 2009, more than two-thirds of all investment in research and development was allocated to water services including water use, wastewater management and water resource management (WRM).

Since 1994 significant progress has been made in reducing the water services backlog in South Africa. Between 1995 and 2003 approximately 9 million people gained access to adequate water supplies although progress in eliminating the backlog of other water services, such as sanitation, has been slower than anticipated. The March 2004 figures show that 17.1 million people still lacked access to basic sanitation services, 4.2 million had access only to VIP toilets and 26.1 million had access to flush toilets. Between 2002 and 2018 the percentage of households with access to improved sources of water increased by less than 4% (growing from 84.4% to 88.2%), while between 2002 and 2019, through the efforts of government, support agencies and existing stakeholders, the percentage of households with access to improved sanitation increased by 20.4% (growing from 61.7% to 82.1%) (http://www.statssa.gov.za/?p=13908).

Rural water supply and treatment

The publication of the 2002 White Paper (DWAF, 2002) on water supply and sanitation policy resulted in a shift towards decentralising the water services sector. In 2003, in line with the Constitution, responsibilities for services provision were devolved to local government. To speed up the provision of water services in rural areas, the Department of Water Affairs (DWA, now DWS: The Department of Water and Sanitation) established a national Community Water Supply and Sanitation Programme. To support this initiative, the WRC set up a dedicated research programme on rural water supply and treatment. Over the years, research commissioned under this programme has provided practical solutions to rural water supply challenges which include access to safe water, technical design flaws, poor water quality, poor operation and maintenance and the need for rehabilitation. Some of the key research contributions to rural water supply and treatment are described below.

Promoting domestic water security through rainwater and greywater harvesting

Over the years, various strategies and means have been explored to improve water availability and security of supply to rural households in South Africa. The main focus of research has been on rainwater and greywater harvesting systems, including investigations of yields, quality of the harvested water and recommended use/treatment options, as well as wider acceptability and adoption of these systems by households. In addition, recommendations have been formulated as to how to overcome some of the barriers identified by various projects (Mwenge Kahinda et al., 2008*; Mannel et al., 2014*; Carden et al., 2018*). Such information supports the formulation of policies to enable the wider rollout of these systems in under-developed communities. Furthermore, guidelines and manuals developed under these projects projects assist in the development of national standards in support of the national water-use-efficiency imperative.

Figure 3. Rainwater harvesting has been a significant coping strategy for especially rural communities during times of drought. (Credit: WRC archives)

Water treatment for rural communities

Various methods of treating water in rural communities have been studied and developed by the WRC. These methods range from simple household filtration devices to more advanced decentralised (package plant) water treatment systems (Voortman & Reddy,1997*; Pillay, 1998*; Modise & Krieg, 2004*; Potgieter et al., 2011*). Research has shown that decentralised point-of-use (POU) treatment solutions are preferable to centralised systems as they can be operated by individual families at their homes. A guideline document prepared by Momba et al. (2013*) summarises the performances of some of the POU devices available in South Africa, and provides guidance to users on both selection and use of these units under local conditions.

A survey done in 2016 (Korlam et al., 2016*) showed that the use of package plants for drinking water treatment in rural areas is common, and that a total of 69 types of drinking water package plants were in use. Since the early 1990s, the WRC has made significant investment in researching membrane technology for rural water treatment. For some 30 years the WRC has funded the very important studies undertaken by the Institute of Polymer Science at Stellenbosch University into the use of membrane technology for the supply of water to rural and urban communities (Jacobs et al., 1999*). The outcomes from this research have led to the development of a point-of-use Rural Water Filter (RWF) prototype (African Centre for a Green Economy, 2018*). Through funding support provided by the Department of Science and Innovation (DSI), the prototype was developed further and optimised for demonstration in rural households in the Capricorn District Municipality and in the Bizana Local Municipality in South Africa. These demonstrations showed that this technology could assist in meeting the South Africa's constitutional requirement that the State should provide potable water at the level of individual households (Department of Science and Innovation, 2014).

Figure 4. WRC-funded research projects have led to the development of several small desalination plants for rural communities, such as this plant at Madibogo Primary School, in North West, which is used to treat brackish groundwater. (Credit: Lani van Vuuren)

Drinking water treatment and water quality assessment

The release of poorly treated effluents into water resources used for drinking water production has long been identified as the main cause of aesthetic problems, and also health problems on account of pathogens and polluting chemicals. Consequently, since the early 1960s, water technologies capable of reducing the risk associated with the presence of these compounds has been a subject of intensive research in South Africa. Similarly, the intense drought of the 1960s prompted research into diversification of water sources for municipal drinking water supply. In addition to the development of measures to treat poor quality surface water resources, innovative technologies were sought for treating sources of differing qualities. Soon after the establishment of the WRC, an important epidemiological study was commissioned to examine the potential effects on health that might arise from the consumption of reclaimed water (Bourne et al., 1987*; Water Research Commission, 1974*). Findings from this study on the further treatment of wastewater effluent for potable reuse, a process termed water reclamation, paved the way for the worldwide adoption of reuse as an alternative source of drinking water supply.

In parallel with the water reclamation research, various pilot-scale investigations into seawater desalination were commissioned (Strohwald, 1992*). The late 1990s were the focus of water treatment technology research and innovation in South Africa in order to meet the new democratic government's aim to extend water services to previously disadvantaged communities. Numerous investigations into the development, optimisation and adoption of various innovative drinking water treatment processes for the removal of contaminants from conventional raw-water sources were funded by the WRC. These included coagulation/flocculation (Pryor & Freese, 1998*), dissolved air flotation (Gehr et al., 1991*), disinfection (Solsona & Pearson, 1995*), filtration (van Beek & Haarhoff, 1997*), membrane technology (Jacobs et al., 1999*), and other bio-based techniques, such as biofiltration (van Niekerk & Rudert, 1999*). WRC-funded research over the years into the improvement and advancement of the science and technology of water treatment has been hailed as a major triumph in water quality regulation and public health protection (WRC 2014*).

The South African water sector also faces the challenges arising from the discovery of new pollutants. Recently, there has been increasing concern about the presence in drinking water of so-called 'contaminants of emerging concern'. Among these are endocrine disrupting compounds (EDCs) which have been studied extensively since the beginning of the new millennium (WRC & TWZ, 2003). The initial research was undertaken at a time when very little was known about the occurrence of EDCs, and their detection, health effects and treatment in water sources, and therefore a dedicated EDC Research Programme was launched by the WRC in 2005 (Burger, 2005*) to coordinate and extend current capacity in order to research EDC and its monitoring in the country. Under this programme, the WRC has continued to support research that tracks the emergence of new EDCs, characterises associated risks, and develops and tests various treatment options for their removal from water for potable use (Genthe & Steyn, 2008*; Meyer et al., 2014*; Aneck-Hahn et al., 2017*; Coetzee et al., 2018*; Petrik et al., 2020*).

WRC research dedicated to tracking the emergence of newly recognised hazards and substances of concern in raw and final, particularly those associated with endocrine disrupting effects, has greatly strengthened the drinking water quality regulatory environment in South Africa. During the 2020/21 review period EDCs will be included in the South African drinking water quality standards (SANS 241). Furthermore, the knowledge of emerging contaminants has sparked renewed interest in the testing, demonstration and adoption of advanced water treatment technologies, such as reverse osmosis, advanced oxidation and nano-based technologies (Metcalf, et al., 2014*). More details concerning the management of water quality are presented in Chapter 4.

Guidelines, manuals and capacity building in water supply and treatment

WRC-led capacity-building initiatives concerning water supply management have focused on two interrelated concepts: (i) strengthening the capacity of water-services institutions to deal more effectively and efficiently with all aspects of sustainable water supply, including the creation of a favourable policy environment and the management of technical and financial aspects; and (ii) assessment and development of the human and infrastructure resources needed for satisfying all the regulatory requirements for water-services provision.

The Masibambane Water Sector Support programme of DWA (now DWS), in partnership with the WRC, has played a critical role in supporting capacity-building for rural water supply and sanitation in South Africa (DWA, WINSA, & CSO, 2013). A series of lessons series aimed at capacity building in the water sector have been published through the Water Information Network-South Africa (WINSA), a learning-sector forum under the Masibambane programme, which until 2013 was located within the WRC. In 2008, the programme won the category for innovative partnerships between government, private sector and civil society at the very first All Africa Public Service Innovation Awards (AAPSIA) hosted as part of the sixth African Conference of Ministers for Public/Civil Service (Department of Water and Sanitation, 2008). The AAPSIA has also played a critical role in capacity building through a number of training and technology transfer workshops, briefs (policy, ministerial and parliamentary), guidelines, manuals and tools aimed at improving municipal capacity for implementing conventional and advanced water treatment schemes, managing risks, and understanding technical and financial aspects of water supply management. Below are some of the key WRC-led capacity building initiatives that have shaped the landscape of water supply management in South Africa.

Improving understanding of water treatment costs

In order to help municipal officials to understand the technology and costs of treating water for drinking, the user-friendly models WATCOST and REUSECOST were developed (Swartz et al., 2013*; Swartz et al., 2014*) for conventional and advanced drinking water supply systems respectively, as well as the accompanying manuals. These manuals serve as reference documents and contain tables and graphs of costing information for water supply and reuse projects. The manuals provide step-by-step guidance on the use of the models to estimate the costs of new and existing projects, total costs as well as the costs of specific components. The models can be used for estimating first-order capital and operating costs of water supply systems, including the costs of determining the approximate values of existing water treatment systems and of upgrading.

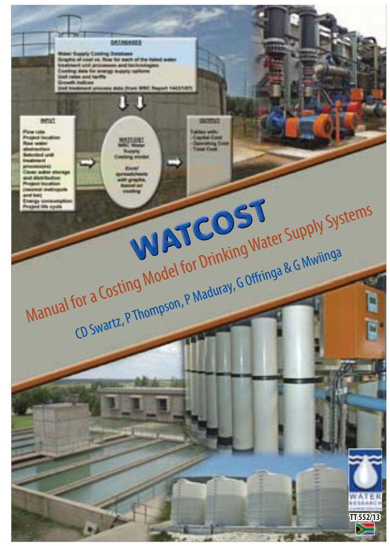


Figure 5. Tools such as WATCOST assist municipal officials to understand the technology and costs of treating water.

Guidance on chemicals used for treating drinking water

On account of the lack of information on drinking water chemicals and standardised testing procedures for water quality control, a number of projects were commissioned in the 2000s. The manual prepared by Freese et al. (2004*) for a project conducted by Umgeni Water in conjunction with the WRC describes testing methods for coagulants, pH adjustment and stabilisation chemicals, oxidants and disinfectants, activated carbon and fluoridation chemicals. A follow-up project completed in 2009 (Wilson & Trollip, 2009*) resulted in the adoption of 46 new standards covering the majority of drinking water treatment chemicals used in South Africa. Recommendations from these studies also led to the inclusion of water treatment chemicals to be regulated under SANS 241, the drinking water quality standard (SABS, 2015).

Water-safety planning

Following a 2004 recommendation by the World Health Organisation (WHO, 2005), water safety planning was adopted worldwide for drinking water quality management. This approach was first formally adopted in South Africa in 2008 as part of the Blue Drop water quality regulation programme (DWS & WRC, 2015). Since that time, the WRC has funded a number of research projects aimed at developing manuals and tools for providing guidance and building capacity for water-safety planning by municipalities (Thompson & Majam, 2009*; Jack & de Souza, 2012*). Apart from application of this concept to drinking water quality management, the WRC has funded other projects demonstrating the application of this concept in domestic water quality management for both potable and non-potable uses (Moodley et al., 2019*) and also for the management of water quality in swimming pools (Pieters & Horn, 2020*).

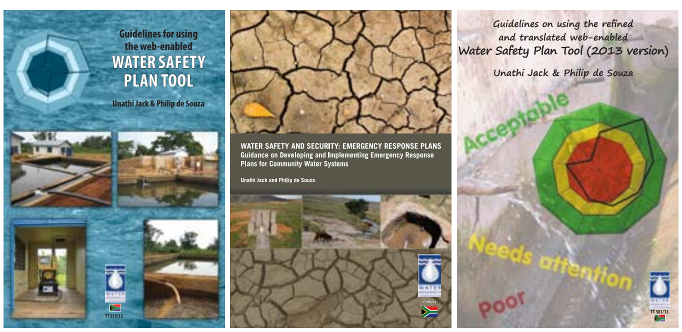


Figure 6. The WRC has funded several projects over the years aimed at improved water safety.

Guidance on implementing desalination and water reuse projects

South Africa mainly relies on surface-water resources to meet water demands, although it has been recognised that in many areas the increasing demands cannot be met by conventional sources only (Water Research Commission,1974)*. Research into the use of water reclamation to augment water supplies in South Africa was initiated in 1962 by the National Institute for Water Research (NIWR) of the CSIR and was continued by the WRC soon after its establishment (Hattingh, 1977).

The first guideline document on planning, design and implementation of a water-reclamation scheme was developed in 1982 by PJ Meiring and Partners (1982*) through WRC-funded research. At that time, the costs of large-scale development of unconventional sources of supply such as water reclamation and seawater desalination were perceived as far outweighing the benefits. Research that followed focused on understanding the costs of water reclamation and desalination with a view to the development of cost-effective technologies. Subsequently considerable investment was made into membrane research. Work done within this portfolio has been used as the basis for the strategic move towards diversifying water resources, first mentioned in the 2004 National Water Resources Strategy document. In 2006, a guideline document supporting the implementation of desalination was published (du Plessis et al., 2006*) and a revised water reclamation guide drawing on accumulated knowledge is currently under development.

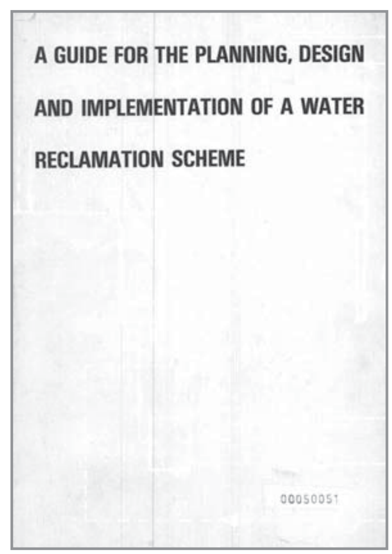

A GUIDE FOR THE PLANNING, DESIGN AND IMPLEMENTATION OF A WATER RECLAMATION SCHEME

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Figure 7. The first guideline on the planning, design and implementation of a water-reclamation scheme, published by the WRC in 1982.

Management of water-treatment-plant residues

Historically, the sludge generated from drinking water treatment was either disposed of back into the water source from which it came, and/or sent to a landfill site for disposal.

Deterioration of source water quality due to landfill-based discharges prompted promulgation of stricter regulations. This led to the development of guidelines for the management of water treatment residues (Mokonyama et al., 2017*) to assist municipalities to comply with current legislation concerning sludge management,

Across the country there is growing momentum to addressing present day and possible future challenges and emerging threats to drinking water supplies. As drinking water production is subject to many regulations, the challenges are becoming increasingly complex. Therefore, to safeguard consumers there is the need for continuous evaluation of both the performance of existing technologies, as well as the development of new ones. Apart from meeting technical performance criteria, focus should also be on developing technologies that are sustainable, that is, they meet environmental, cost and energy efficiency objectives. The increased occurrence of emerging contaminants in source water requires the establishment of an early warning water quality surveillance programme.

WASTEWATER RESOURCES

Background

Sustainable wastewater management is a complex subject with interplay between an array of social, environmental, institutional, economic and technical issues. The importance of wastewater needs to be viewed in the context of human health and environmental integrity; the number and diversity of interests, both local and cross-border; competition for water resources; the technological choices for supply and treatment of wastewater; the management and regulation of resultant outflows; the reliable delivery of water quality and quantity to multiple users; and the use of price and licensing to allocate and cost water. Furthermore, sustainable wastewater management is a complex multidimensional discipline on account of the sheer size of the industry and its assets. On account of these complexities, the WRC has a rich history of research into and the development of technology for sustainable wastewater management.

The development of the ability to remove nutrients (nitrogen and phosphorus) from municipal waste waters became critically important when the rivers draining the industrial and commercial centre of Gauteng became highly eutrophic. Although the WRC had funded research in both chemical and biological nutrient removal (BNR), the emphasis had been on biological nutrient removal, as chemical removal would contribute to salinisation of receiving waters. Research into biological nutrient removal was first supported by the WRC in 1973, very soon after Dr JL Barnard first found that phosphorus could be removed by bacterial activity (Ekama et al., 1984*).

Since that time, research has been funded at various institutions, initially the CSIR, and subsequently the Department of Civil Engineering at the University of Cape Town (UCT), with the Johannesburg City Council playing a leading role in both the understanding and the development of the process. This work led to a number of publications, one of the more notable being the report entitled ***Theory and design of nutrient removal activated sludge processes*** by Ekama et al. (1984*), for which there has been widespread international demand. On account of their work, the researchers at UCT formed part of the team that developed Activated Sludge Models 1 and 2 for nutrient removal for the International Association on Water Quality (IAWQ) (Henze et al., 1987; Henze et al., 1995). These have become the internationally accepted models for biological nutrient removal (Gernaey et al., 2004). In recognition of the fact that there were many wastewater treatment plants in South Africa that did not have the capability of removing phosphate biologically, the WRC funded research leading to the publication of the ***Guidelines for chemical phosphate removal from municipal wastewaters*** (WRC, 1986*).

Tools, manuals and guidelines in support of wastewater best practice

A number of tools, manuals and guidelines have been developed by the WRC to support decision-making and best practice in the wastewater sector. These products include operation and maintenance manuals (du Pisani, 1998*; Lilley et al., 1997*; Swartz et al., 2009*), sludge management guidelines, (Snyman et al., 2006*; Swartz et al., 2009*; Herselman et al., 2009*) and tools for risk-based planning and selection of appropriate technology (Van der Merwe-Botha et al., 2016*). Most of the material used for capacity building and training for operation and maintenance in the wastewater sector in South Africa is currently based on knowledge generated in WRC-funded projects. In this regard, WISA's (Water Institute of Southern Africa's) continuous professional in-house training courses on sustainable operation and maintenance of wastewater treatment plants (WWTPs), and the management of domestic wastewater sludge, are generally based on knowledge developed by the WRC.

Several operation-and-maintenance manuals in support of sustainable WWTP operation have been compiled for the sector. The focus for most of these manuals has been on strengthening best management, operation, maintenance and inspection practices and also on training. A comprehensive list of these manuals and guidelines is available in the South African Guidelines, 1985-2010. The recently developed guide for wastewater treatment technologies (WRC Project No. K8/1106*) was developed in partnership with the South African Local Government Association (SALGA) as a simple tool in support of capacity building and training, and has been positively received by the sector.

Figure 8. Treatment technologies – a basic guide, one of the tools developed through WRC funding.

Sludge management

Sludge is a key component of sustainable wastewater management, in fact, wastewater treatment plants can be thought of as sludge factories. WRC-funded research on sludge has been documented in a number of volumes and the first edition of the volume ***Permissible utilisation and disposal of sewage sludge*** (WRC Report no. TT 85/97*) was published by the WRC in 1997. This was superseded by a series of Sludge Management Guidelines (Snyman et al., Swartz et al., 2009; 2006; Herselman et al., 2009*), which is currently used by authorities responsible for water and environmental affairs to stipulate the regulatory requirements for sludge management Authorisations. The Guidelines consist of five volumes, authored by Snyman et al (2006*): Volume 1 and Herselman et al (2009*): Volumes 2 to 5.

Figure 9. The sludge guideline series used to manage, classify and regulate sludge in South Africa.

Beneficial agricultural use of sludge

In addition to the Sludge Management Guidelines stipulating the regulatory requirements for sludge management, a database model for the beneficial agricultural use of sludge in support of the food security has been developed by Tesfamariam et al. (2015*). The database model has three main components: sludge application rate advisor (SARA), sludge cost benefit advisor, and simple field heavy metal mass balance advisor. SARA provides practical decision support for the sector in terms of quantification of the fertiliser value of sludge, and includes cost comparisons of alternative beneficial agricultural uses of sludge.

Figure 10. Sludge pellets, typically used in agriculture applications. (Credit: Lani van Vuuren)

Wastewater risk-abatement planning (W_2RAP)

South Africa needs effective and efficient systems for providing wastewater services if it is to rise above current challenges and provide high-quality services to all its people. The most effective means of consistently ensuring that the infrastructure for dealing with wastewater is functional and effective is through the use of a comprehensive risk assessment and management approach that encompasses all components of the wastewater system. Fundamental to successful execution of such activities is proper planning.

In 2009, the DWS introduced incentive-based regulation schemes, the Blue Drop Certification (BDC) for drinking water services and the Green Drop Certification (GDC) for the provision of wastewater services by municipalities. In support of this programme, the WRC developed the guideline document authored by Van der Merwe-Botha & Manus (2011*) and spreadsheet/web-based tools to assist water services authorities with Wastewater Risk Abatement Planning (W_2RAP) activities (WRC Project No. K5/2217/3*). The implementation of W_2RAP was undertaken in response to the need to support DWS's GDC programme.

The WRC has developed tools to guide the selection by municipal officials of appropriate wastewater treatment technology (Jack et al.,2016*). A number of training workshops have been conducted in the use of these tools and plans are under way in partnership with WISA to expand this dissemination programme. Both the risk-based planning (W_2RAP) and decision support (W_2DST) tools can be accessed via the RiskQ website.

Figure 11. Some of the various wastewater risk abatement tools developed by the WRC.

Technological innovations

Decentralised wastewater treatment systems

Technological innovations for sustainable wastewater and sludge management have been developed by WRC-funded researchers (Cowan et al., 2016*; Musazura et al., 2018) as well as tools, manuals and guidelines in support of decision-making and best practice. These technological innovations have been designed to deal with the continuous challenges associated with achieving more stringent effluent discharge standards and reduced energy consumption.

In many countries, including South Africa, large-scale centralised treatment systems are no longer the most viable option for urban wastewater management). For more than 15 years the WRC has focused on decentralised wastewater treatment systems (DEWATS) because these systems allow recovery of nutrients and energy, saving of freshwater, and access to water in times of scarcity. The research and development work has been undertaken with the support of the Water and Sanitation Department of eThekwini Municipality and has included setting up a pilot plant at Newlands Mashu (Durban). Besides providing a site for building water-sector capacity on DEWATS, it has opened up further research and development opportunities for integrating DEWATS with agriculture as part of the Water-Nutrient-Food Nexus in support of household food security (for more information, see Chapter 5).

At present, plans are underway in partnership with Bremen Overseas Research and Development (BORDA) to roll out more DEWATS plants for households outside the main sewer network within the eThekwini municipalities. Based on monitoring data from a WRC-supported project (Arumugam & Buckley, 2020*), eThekwini has been allocated a water use license to implement DEWATS systems in the areas outside the sewer network.

<u>Energy efficiency within wastewater services</u>

About 55% of energy used in the South African water cycle is for wastewater treatment, the bulk of this energy being used in aeration of biological processes (Table 1). Up to 15% of wastewater energy demand can be offset by biogas generation from sludge, however the combined heat and power could deliver additional energy-efficiency gains of between 5% and 25% in the water cycle, while still adopting best practices (Musvoto & Ikumi, 2016*).

Table 1: Energy consumption at various stages in the South African water-supply chain

Process	*Min. (kWh/Ml)*	*Max. (kWh/Ml)*
Abstraction	0	100
Distribution	0	350
Water treatment	150	650
Reticulation	0	350
Wastewater treatment	200	1 800

WRC-supported research on the generation of energy from various waste streams has identified sectors having the greatest potential for energy recovery. These waste streams include the formal and informal animal husbandry sectors, the fruit and beverage industries, and domestic blackwater (sewage). An estimated 10 000 MWh/annum is potentially recoverable from wastewaters within South Africa, representing 7% of the national power supply in 2009. Furthermore, recent analysis of the status of anaerobic digestion in South Africa conducted by the WRC (van der Merwe-Botha et al., 2016*) has also indicated that the total biogas production potential from WWTPs is some 283 000 m^3/day, translating to 658 000 kWh/day of electrical energy, which could result in an estimated potential saving (at 60 cents per kWh for electricity) of R144 million per annum. What is more, studies on the implementation of energy efficiency in conjunction with energy generation within the South African wastewater sector have demonstrated a potential saving in energy of between 50% and 78%, as well as improved effluent compliance through implementation of various measures (Zvimba & Musvoto, 2020*). At the time of writing, the WRC in partnership with the Deutsche Gesellschaft für Internationale Zusammenarbeit (GIZ), a German Agency for International Cooperation, was planning to conduct a nationwide energy-use benchmarking exercise for the whole sector to guide municipalities in planning future energy management.

SANITATION

Background

The WRC became actively involved in funding research into basic sanitation in the late 1980s in the aftermath of the United

Nations Water Supply and Sanitation Decade (1980-1990), which had determined that water supply and sanitation were the main problem areas that required research in developing countries. Experience gained in South Africa during that decade had indicated that problems in service delivery were centred on social, cultural, gender, training, institutional and financial issues, with technological issues being of relatively minor importance.

In response to the key problems identified, and recognsiing that South Africa is a waterstressed country, post-apartheid sanitation research focused on non-sewered sanitation technology, specifically dry (waterless) sanitation. At that time many South Africans were without adequate sanitation or had challenges with affordability, good hygiene measures, provision of potable water, and appropriate sanitation, which were key to preventing disease outbreaks and environmental pollution. On the other hand, research products at the time were limited to the development of technical manuals for improved construction techniques and/or modification of latrine structures (Solsona, 1998*; Bester & Austin, 2000*).

WRC research on sanitation (1994 to 2000s)

Non-sewered latrine technologies were widely used in the developing world at the time and included aqua privies, bucket latrines, composting toilets, ***feuillees*** or ditch latrines, Blair or ventilated improved pit latrines (VIP) latrines and several others (Solsona, 1998*). Earlier policy documents made reference to VIP latrines as a minimum acceptable standard, leading to the accelerated provision of VIP latrines throughout South Africa (Department of Water Affairs and Forestry, 1994; National Sanitation Task Team, 1996). Consequently, even today, in many water service authorities (WSAs) VIPs still remain the minimum standard of sanitation provided. Recent statistics indicate that there are around 1.2 million household VIP units currently in use (Statistics South Africa, 2019). At the time of implementation, the VIP latrines were thought to be the most appropriate and suitable technical option (Solsona, 1998*), for the following reasons:

- The technology does not require water, which is a scarce resource.
- The technology does not require laying of sewers, which are costly.
- VIPs were considered to be affordable both for municipalities and customers in comparison with fully reticulated sewerage systems.

Figure 12. There are an estimated 1.2 million household VIP units in South Africa, located both in rural and urban areas. (Credit top: Lani van Vuuren and bottom: Kathy Eales)

At the turn of the millennium, challenges were being experienced on the ground with VIP latrines. Some of the early challenges centred around design and construction issues included the inability to move latrines once they were full, accessing the slab for emptying, and user dissatisfaction related to perceptions of odour. The research commissioned by the WRC during this period focused on these challenges.

The SanPlat Toilet project was undertaken through WRC-funded research with the aim of introducing alternatives to VIP latrines (Solsona, 1998*). The SanPlat concept was designed to tackle the less desirable aspects of VIP latrines, specifically the challenges associated with ventilation (through vent pipes) and access for emptying the accumulated faecal sludge. Unlike the VIP latrines, the SanPlat latrine design was sealed to prevent malodours. The project provided the technical specifications for the design of the SanPlat but there was no post-implementation evaluation of the technology, and it appears that the technology did not achieve widespread implementation in South Africa (Solsona, 1998*).

In another project, the WRC provided support for a research proposal submitted by the Greater Johannesburg Metropolitan Council to investigate a locally developed dry sanitation system known as the ***Enviro Loo*** (Stewart, 1998*). At the time, the use of composting latrines was limited, as VIP latrines were the basic minimum standard. Although a number of the composting units were implemented nationally, the research project represented the first local, large-scale independent trial and assessment of the technology. The research pointed out that while user acceptance was higher than for communal chemical toilets, the system did not compost the faecal sludge but dehydrated it, meaning that the sludge was not beneficiated to the intended end-product.

To better understand how to engage communities in the provision of sanitation, the WRC funded research aimed at evaluating on-site sanitation systems. The findings were repackaged by the authors into a handbook (Bernhardt Dunstan & Associates, 1998*) to assist communities and those involved in sanitation policy and practice to achieve affordable, sustainable sanitation systems.

In 1999, the WRC initiated a project which was undertaken by Pearson & La Trobe (1999*) to address the challenge of latrines becoming full, and the subsequent disposal of faecal sludge. This research project was one of the first at the WRC to investigate what we now know as a Circular Economy approach, where the emphasis is on incentivising recycling, in this case the conversion of sludge into agricultural compost.

In what was a prelude to later scientific undertakings through the WRC, the research showed that pit latrine sludge applied in windrows still showed evidence of microbiological contamination at the end of the process, and that the faecal sludge had a significantly higher phosphorus content in the final compost than sludge from septic tanks.

Research support for rural sanitation infrastructure programmes (2000s to mid-2010s)

It is acknowledged that the VIP is appropriate sanitation technology provided that it is used appropriately and is routinely serviced. The technology has resulted in a significant improvement in the provision of sanitation to local communities and is vastly superior to the unimproved pit latrine, particularly regarding hygiene and user acceptability. The research focus in the 2000s was mainly a demand-responsive approach and to address the challenges experienced at that time, namely:

- New municipal boundaries, some with large urban centres and others with large rural components, and the associated challenges,
- VIP latrines and the management of the faecal sludges from full pits,
- Poor user acceptance of non-sewered dry sanitation, i.e. VIP latrines, and
- Lack of design standards for the construction of latrines.

Dry sanitation technologies

In the early 2000s, several research products were developed based on projects commissioned in the late 1990s. These included the development of technical standards for the design and construction of VIP latrines (Bester & Austin, 2000*), hygiene awareness for rural water supply and sanitation projects (Duncker, 2000*), using multimedia for the communication of WASH (***WAter, Sanitation and Hygiene***) issues (Ward et al.,2000*), and understanding sludge accumulation rates in various non-sewered systems (Norris, 2000*).

After municipal boundaries were revised in 1999/2000, the emptying and disposal of sludge from latrine pits became an operational challenge, particularly in the rural areas of larger municipal areas centred around major urban centres. One of the first studies commissioned by the WRC into the subject of sludge accumulation in septic tanks, biological digesters and pit latrines was to provide localised data, all data having previously been sourced from international studies (Norris, 2000*). The WRC's research provided guidelines for such systems based on the data collected. Using Kamiesberg Local Municipality as an example, the WRC evaluated the effects of the restructuring of municipalities on the feasibility and financial ability to effectively perform ***operation and maintenance*** (O&M) of sanitation facilities (Atkinson & Ravenscroft, 2002*). Guidelines were also produced to assist municipalities in selecting the most appropriate form of sanitation (Howard et al., 2000*).

Exploration of alternative solutions to VIPs

The binary engineering paradigm, either reticulated sewerage or VIP provision, had its shortcomings and the mid-2000s saw the exploration and emergence of alternative approaches. A large proportion of the research was undertaken in partnership with eThekwini Municipality, which had seen its municipal boundaries increase substantially and was required to serve a larger previously unserviced population and to maintain non-sewered sanitation systems in the inherited rural areas. While the WRC-funded research undertaken by Eslick and Harrison (2004*) showed that shallow sewers can be installed at significantly reduced capital costs using a waterborne approach, several challenges were noted. These challenges included legal issues related to land tenure, compliance with the National Building Regulations (NBR), and social and political influences related to water supply (Eslick & Harrison, 2004). At about the same time, WRC-funded research had begun to evaluate ***Anaerobic Baffled Reactors*** (ABRs) for low-cost, waterborne sanitation (Foxon et al., 2004). Research into Decentralised Wastewater Treatment Systems (DEWATS) continued and continued, progressing from pilot-scale to demonstration-scale and currently to implementation from pilot-scale to demonstration-scale and currently is in the implementation phase.

In the mid-2000s 'ecological sanitation' (ECOSAN) was evaluated as an alternative approach to VIP latrines. The premise behind the technology is that separating urine and faeces at the pedestal interface would result in a drier and more manageable end-product, which could be recycled into agricultural products. Research conducted by Austin et al. (2005*) aimed to provide a better scientific understanding of the technology, as well as its operational limitations, which were neither widely known nor well-understood at the time. Austin (2006*) and colleagues later provided technical guidelines for the design, operation and maintenance of ***Urine Diversion*** (UD) systems, as reported on for VIP latrines by Solsona (1998*). User perceptions were subsequently evaluated (Duncker et al., 2006*). The study showed that most of the users accepted the UD toilet mainly because they did not have a choice or have the funds to buy a flush toilet. User preferences were still to eventually have flush toilets and the handling of faecal sludge by the community was perceived as difficult in comparison to that for VIP latrines.

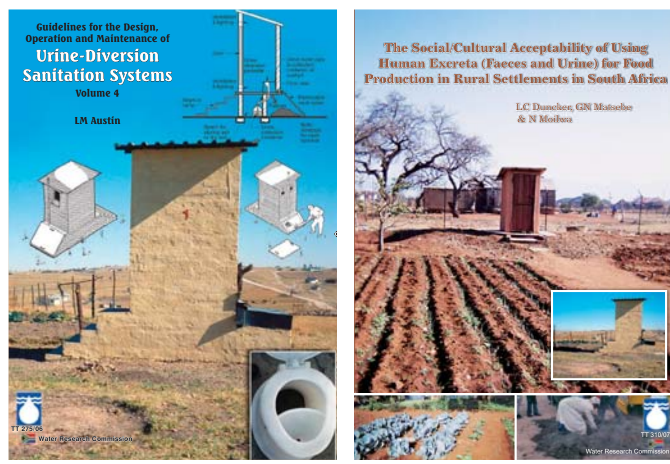


Figure 13. In the mid-2000s, ecological sanitation was evaluated as an alternative approach to VIP latrines.

Buckley et al. (2008*), characterised the faecal sludge accumulating in urine-diverting dry toilets (UDDTs). The aims of the project were as follows: to provide a scientific basis for the design and operation of UDDTs as used by the municipality; to evaluate the effectiveness of system in improving the well-being of the user community; and to determine the fate of the eggs of ***Ascaris***, a roundworm parasite, in the faecal sludge. The most significant outcome of this research was the development of a new technique, the ammonium bicarbonate (AMBIC) protocol, for detecting parasite eggs in soil and faecal samples (Buckley et al., 2008*).

Groundbreaking research into dry-sanitation latrines

Since 1994, large-scale infrastructure programmes have been implemented to build VIPs to achieve national service-delivery goals. Current estimates indicate that around 30% of the entire South African population rely on VIP toilets and their derivatives (Statistics South Africa, 2019). A national audit of water and sanitation projects conducted on behalf of the then Department of Water Affairs and Forestry (now DWS) indicated that in 60% of the facilities surveyed, municipalities were conducting reactive maintenance only, while 40% of municipalities had inadequate maintenance capacity (SALGA, 2009). Many thousands of these dry sanitation systems were reaching their capacity faster than anticipated. A tipping point was being reached as many municipalities did not have operation and maintenance procedures, budgets and plans for VIP toilets with some pits requiring emptying as frequently as twice a month (Mjoli, 2010*; Still & Foxon, 2012*).

In the early 2000s, the WRC strategically invested in developing innovation around the faecal sludge management (FSM) supply chain. At the same time, the eThekwini Municipality, which has the City of Durban as its core, was undertaking an emptying programme on all VIP latrines, 60 000 of which were inherited from local entities when its municipal boundaries were expanded. Many of the pits encountered during the programme were reported to be more than 10 years old and in urgent need of emptying (Brouckaert et al., 2013). This task could only be achieved by manual excavation as the latrines contained various volumes of detritus content (Still & Foxon, 2012*). This led to the WRC in partnership with eThekwini Municipality and a number of research institutions attempting to improve the knowledge base for dry sanitation by the three-pronged strategy as described in the following WRC reports:

- Volume 1: Understanding sludge accumulation rates in VIPs and strategies for emptying full pits (Still & Foxon, 2012*).
- Volume 2: Scientifically elucidating the treatment processes occurring in VIP latrines and their variants (Still & Foxon, 2012*).
- Volume 3: Developing pit emptying technologies (Still & O'Riordan, 2012*).

Figure 14. Manual pit emptying taking place in eThekwini Metro. (Credit: Lani van Vuuren)

Early in the 2010s, the issue of FSM began to bring further attention to non-sewered sanitation and the role that technology can play in the provision of sanitation services. Recognising that the provision of waterborne sewerage cannot match the rate of growth of backlog in the provision of sanitation arising from the increasing urbanisation and the scarcity of financial resources, FSM came to prominence, with South Africa playing a major role in shedding light on this global challenge. The second FSM Conference was hosted in Durban in 2011. The conference dealt with themes such as understanding what happens in pit latrines, how sludge accumulates and degrades and how it can best be managed. This included the beneficial use or conversion of faecal sludge into value-added products that could later become part of the circular economy research strategy at the WRC. The WRC would continue to play an important role in contributing to subsequent FSM Conferences held in Hanoi, India and in Cape Town, for which WRC staff played a key role in conference co-ordination (Faecal Sludge Management Alliance, 2021).

In 2013, the WRC and the Bill & Melinda Gates Foundation (BMGF) partnered the Sanitation Research Fund for Africa (SRFA) Programme, which is aimed at growing the technical capacity and knowledge base needed to support effective FSM in sub-Saharan Africa. The programme is aimed at providing FSM solutions that are based on scientific evidence using the research strategy previously employed with eThekwini Municipality. Twelve institutions from eight southern and east African countries were awarded research grants by the BMGF, all managed by the WRC's research, development and innovation template through the SRFA Programme.

Since 1994 significant strides have been made in the provision of sanitation although significant numbers of South Africans are still not served and this has been exacerbated by secondary backlogs. The research undertaken through the WRC and its partners has shown that, while users may aspire to full waterborne sanitation, this is not technically feasible. On the other hand the implementation of the VIP programme has received limited user acceptance and there are challenges in emptying and disposal of accumulated faecal sludges. Compounding these challenges is the issue of water scarcity. Consequently, universal access to waterborne sanitation may never be realised on account of the availability of water and also because of the prohibitive costs.

Recognising the need for paradigm disruption, the WRC initiated the ***Sanitation Transformation Initiative (SANITI)*** – the acronym serving as a play on the word ***sanity*** and the wording aimed to bring prominence to the insanity of doing the same thing over and over again and expecting a different result. There remains no silver bullet to sanitation, with toilets being but one part of the sanitation chain. What is required is a strategic re-think of how sanitation is provided; a change to a systems approach in which all aspects of sanitation are inter-related and inter-dependent; and the adoption of business models, such as circular economy and market entry, as well as market-based research, as part of the approach as indicated in Figure 15.

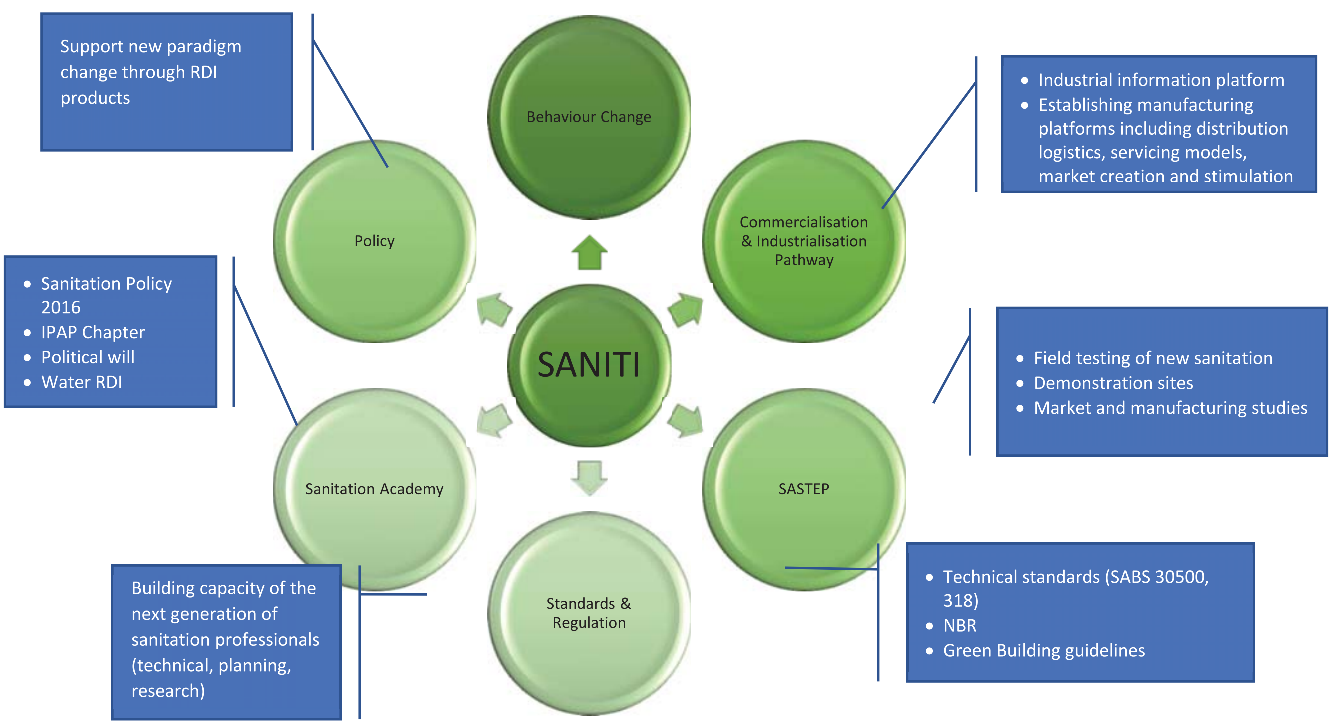


Figure 15. SANITI – the systems approach used that focuses on multi-faceted areas that are inter-dependent and inter-connected.

In disrupting the current paradigm and creating a new market, the national government will have to play a leadership role as well as the roles of enabler and facilitator. It is also about transforming a very entrenched public supply model which will have to evolve if we are to be successful. The WRC will support transforming the sanitation environment towards a new technological environment which will see sanitation going off-the-grid and being associated with a circular economy approach to a new sanitation services market.

CLIMATE CHANGE RESILIENCE

INTRODUCTION

The South African water sector is expected to be significantly impacted by the projected changes in climate. We have already seen evidence of this during the most recent El Niño event (2015/16), and the entire water services chain is vulnerable to the effects of climate change, from the raw water source, through to the purification and distribution processes and subsequent wastewater treatment.

Increased temperatures will affect existing water treatment infrastructure and conveyance systems. In this regard, storage tanks, flocculation chambers, and the pipeline network used for water distribution may be exposed to increased corrosion as a result of higher temperatures. In turn, an increase in extreme events, such as floods, may damage infrastructure. An increase in temperature will also lead to a concomitant increase in water demand and use despite a decrease in available water at the source due to higher rates of water loss, especially from dams. This will result in an increased level of pollutants in water resources, which will translate to an increase in the cost of treatment, an important area for municipalities to be able to put in place the necessary plans to adapt to these changes. All of these changes will be an added burden to municipalities, who are already having to cope with eradicating service backlogs in support of improved service delivery, ensuring proper operation and maintenance of water and wastewater systems and ensuring water security amid rising demand and dwindling water supplies.

To assist with addressing above challenges guidelines dealing with the selection of relevant water sector adaptation technologies and approaches for specific climate change impacts over the short-, medium- and long term have been developed (Dube et al., 2016*). The concept for adaptation articulated in these guidelines is to provide solutions that can be applied across various geographical settings and municipal capabilities, thus setting the basis for adaptation to be planned and applied where and when required, especially in the most vulnerable regions and within suitable timeframes.

Municipalities' role in climate change adaptation

South Africa's national response to climate change is framed by its commitments to the United Nations Framework Convention on Climate Change (UNFCCC) and the Kyoto Protocol. As a signatory to this convention, the national government of South Africa committed to a goal of achieving a 34% reduction in greenhouse gas (GHG) emissions, against a business-as-usual trajectory, by the year 2020. South Africa has also recently signed the Paris Agreement on climate change which emphasizes increasing the ability to adapt and to foster climate resilience.

In line with these commitments, the Department of Environmental Affairs (DEA) has published the National Climate Change Response Policy (NCCRP), which prescribes the means by which these international commitments will be achieved. The NCCRP deals with both climate change mitigation and climate change adaptation. The NCCRP White Paper has recognised local government as an important sphere of climate change mitigation and adaptation. In particular, Section 10.2.6 identifies the key Constitutional mandates of local government that are critical in developing the South African national climate response. These include planning and urban development; municipal infrastructure and services; water, energy and waste demand management, and local disaster response.

When municipalities compose their climate change adaptation response, as they are now being encouraged to do, they should consider their specific local circumstances. The options selected should optimise prevailing and anticipated environmental, social, economic and cultural aspects. Options should also be associated with a favourable economic assessment after accounting for the social components for which monetary returns are not expected. In this regard, rural municipalities are considered to have the poorest adaptive capacity making them more vulnerable to the additional stresses, while large urban municipalities are associated with a higher level of service delivery, thus reducing vulnerability. The Blue- and Green Drop scores also point to the nature of vulnerability in water and wastewater services. A poor score also means that the institution and the service delivery process are highly vulnerable to the impacts of external factors such as climate change. As such, these vulnerabilities have to be dealt with before accounting for climate change.

Water sector bylaws and management of restrictions are currently evolving at a slow pace which does not necessarily cater for the threat of climate change to water service provision but rather attempts to respond to disasters in dire situations. In this regard, plans for implementing climate change adaptation are still failing to make it onto the list of prioritised projects for the municipalities, even though several climate change strategies may have been developed. This often results in failure of cities to respond to disruption in water supply, for example in cases of extended drought, which is a feature of changing climates.

Conclusions and recommendations

Since South Africa is a fully integrated member of the global community, international protocols and obligations to which the country is signatory determine the nature of response adopted by the South African national government. In turn, this needs to be translated into local strategies, programmes and projects to ensure successful implementation. Adaptation technologies and approaches should aim to meet increased resilience to climate change in local government and should not be seen to be compromising local development but rather helping to improve efficiency and sustainability. The science and trends that lead to adaptation selection must be well considered and precise, based on local information. This should in a way help to strengthen South Africa's international obligations to climate treaties in a bottom-up approach and also encourage societal benefits from ecosystem-based adaptation within municipal scales, with adaptation technologies and approaches that are specific to South Africa's vulnerability and sensitivity to climate change. The focus should mainly be on improving the state of services through adaptation, and averting loss and damage as they occur. In highly vulnerable areas, modular structures that can be easily modified should be utilised. Win-win adaptation technologies can also be utilised. These are technologies and approaches that are effective irrespective of the kind of climate change impact that occurs.

Generally, the implementation cycle for adaptation to climate change within the South African local government can be schematically illustrated as shown in Figure 16.

1. Identify CC impacts for which to develop a technological response (Worse case on vulnerability)
2. Selection of suitable adaptation technology (Apply selection criteria)
3. Design of adaptation solution that uses selected technology
4. Implement adaptation approaches which support the adaptation solution
5. Installation of technology for case studies or trials
6. Observations, data collection and analysis during use (Monitoring and evaluation)
7. If analysis generates favourable results go to 8 otherwise return to 2
8. Customise, redesign to improve solution on the basis of analysis results or accept solution as is
9. Installation of updated technology for wider application
10. Awareness and training to ensure continued support and sustainability
11. Build long-term monitoring procedures for adaptation technology and approaches

Figure 16: Implementation cycle for adaptation technologies and approaches.

After implementation, assessment of selected options is necessary. This is to either re-engineer selection options for maximum effectiveness, or to select alternative adaptation options in cases where the first selected option fails to achieve the required results. It is important for municipalities to note that adequate time should be allowed before alternative options are considered. This is to ensure that selected options are indeed inadequate before moving to different options.

The functionality of implemented options can be addressed through the use of a feedback mechanism whereby community residents are able to provide feedback regarding the implemented options. This should provide an avenue for implemented options to be re-engineered after evaluation to ensure that maximum benefits are obtained from them. Other instruments can be used to enhance climate change adaptability within municipalities. For example, it is recommended that the Blue Drop and Green Drop certification programme be reintroduced and aligned to ensure that institutions are indeed adapting to climate change by measuring the performance of water and wastewater treatment works in correlation with the implemented adaptation options. This will enforce adaptation across all regions as municipalities aim to achieve maximum scores on the Blue Drop and Green Drop scales.

However, it must be borne in mind that South Africa is a developing economy; hence there are other competing needs that must be addressed. Service delivery backlogs and the need for socio-economic development take precedence over emerging issues. It is therefore important that climate change response is in line with these two factors. In other words, the funds assigned can be used to address service delivery backlogs and improve the economic standing of the municipal area in such a way that it builds the climate resilience of societies. This requires excellent decision-making when selecting improvement options for the water services sector of any region and will reduce adaptation costs and planning.

Overall, community members have a major role to play in water services adaptation. Knowledge on climate change has to be shared with communities to ensure that they are actively involved when municipalities seek to drive climate change response strategies. Local authorities need to embark on intensive climate change awareness campaigns with the aim of bringing understanding and knowledge to local communities as a forerunner to the introduction of adaptation strategies.

RISK MANAGEMENT AND GOVERNANCE IN WATER AND SANITATION SERVICES

Background

Despite a good legislative framework, democratic South Africa has always faced significant challenges in both the equitable and the sustainable provision of adequate and safe water and sanitation services. Among these challenges, water and wastewater quality risk management failure at water services institutions has been prioritised as it has direct implications to public health. To improve the situation, South Africa's Department of Water and Sanitation (DWS) (water services sector leader and national regulator) and various other public and private water sector partners have undertaken multiple initiatives through the years to assist municipalities with risk management and governance to ensure improved water and sanitation services operation and management. This section provides a brief overview of the research-to-practice journey, from risk management to governance, in municipal water and sanitation services provision. This section only focuses on the role played by the WRC, in collaboration with, inter alia, the DWS, Emanti Management Pty Ltd (a > 51% black owned SME) the Council for Scientific and Industrial Research (CSIR), the Institution of Municipal Engineering of Southern Africa (IMESA), and South African Local Government Association (SALGA), as well as a number of universities.

Effective risk management in water has been considered a priority subject of research for the WRC since establishment. For example, earlier WRC-funded studies on implementation of water reclamation as an alternative municipal water services supply strategy, included a large component on water management (WRC 1974*, Skivington 1997*). Over the years, the WRC has supported the progressive transition from simple operational risk management to risk governance in water and sanitations services. The need for a shift from risk assessment and management to risk governance has been in accordance with international best practices.

Improved risk management in provision of municipal water and sanitation

Following a groundbreaking provincial initiative by the CSIR and the then Free State Department of Local Government and Housing in the early 2000s, in which municipal water quality management across all municipalities of the Free State was introduced using a risk management-based methodology, the very noticeable benefits thereof drew the attention of multiple national parties, including DWS and the WRC. It was clear that a substantial national need existed for well-structured risk-management-oriented water quality management methods for use across all communities by all municipalities both to capture water quality data and to support the better management of provision of safe drinking water and treated wastewater discharge.

The CSIR approach, supported by a water quality data capture and information dissemination tool, had been shown to both assist municipalities to meet their responsibilities, and assist provincial and national departments to monitor, regulate and support municipalities. Consequently, the CSIR team was spun out as the entrepreneurial start-up Emanti Management, and who – with supportive guidance and partnership with IMESA, successfully supported DWS in developing and rolling out a comprehensive municipal engineering oriented electronic Water Quality Management System (eWQMS). eWQMS, an Open-Source web-based tool was developed and maintained by Emanti Management for DWS and starting in 2003 was incrementally rolled out across all of the then 166 municipal WSAs across South Africa. By 2006 eWQMS was providing municipalities and municipal engineers with a user-friendly platform for capturing, tracking and managing both drinking water and treated wastewater quality, and the Regulator with monthly reporting thereon. This significant achievement was recognised locally by National Science and Technology Forum and IMESA awards (2006,2007 & 2008) and by the International Water Associated (IWA) who in 2008 awarded the DWS, IMESA and Emanti team the IWA's prestigious Project Innovation award, first for the Europe Zone (in the absence of an Africa Zone) and then the Global first prize.

Figure 17. Members of Emanti Management and the WRC with the IWA award for the eWQMS in 2008. (Credit: WRC archives)

In 2008, DWS built on the learnings of the five years of eWQMS by extending the water quality risk management methodology encapsulated within the eWQMS a complimentary incentive-based Blue Drop Certification process. In due course, this included the development of DWS' regulatory drinking water quality information system, the Blue Drop System (BDS), which was populated with data loaded by municipalities onto eWQMS. Importantly, an integral part of Blue Drop Certification is the development and implementation of Water Safety Plans (WSPs), as endorsed by the World Health Organisation (WHO) and the International Water Association (IWA) as a risk management based global best-practice.

The WRC became aware that during municipal interactions and feedback from Blue Drop assessments, municipalities were battling with local interpretations and would benefit from a "South Africanisation" of the WSP process, localisation of guidelines for WSPs, and practical peer-based learning opportunities as to the development and implementation thereof. Consequently, a generic Water safety plan for small community water supplies (Thompson and Majam, 2009*) was developed as a guideline for municipalities. The obvious need to further assist municipalities in developing WSPs led to a project led by Emanti Management to develop both spreadsheet-based and eWQMS-based WSP tools for use by all municipalities in South Africa. This would potentially not only reduce the costs to municipalities for preparing WSPs, but WSP information captured via these tools could also be passed onto the BDS for regulatory purposes.

Water safety planning tools

The initial WRC water safety planning tools included:

1. Water Safety Plan Tool (web-based and supportive spreadsheet-based tools, and supports the development and status tracking of a WSP)
2. Water Safety Planning Status Checklist Tool (web-based and supportive spreadsheet-based tools, and allows the user to determine status of water safety planning processes – i.e. Where are we? What have we completed? What must we still do?)

The WRC ***WSP Tool*** was developed to allow a user to complete a WSP, and include the following sections: (1) Formulate the WSP team, (2) Describe the system (source, treatment, storage, distribution, point of use), (3) Assess/evaluate the water system (source, treatment, storage, distribution, point of use), (4) Hazard/risk assessment of the water system (source, treatment, storage, distribution, point of use), (5) Summary of risks and associated prioritization and (6) Identify control measures and associated corrective actions, responsibilities, timeframes, and costs (for subsequent WSP implementation).

The WRC ***Water Safety Planning Status Checklist Tool*** was developed to assist municipalities in understanding all aspects of water safety planning, and rapidly assessing their progress in these activities (i.e. Where are we and what do we still need to do?). This tool considers typical water safety planning steps and asks 5 key questions per step. Based on the answers, a score is calculated, and a colour-coded 'spider-diagram' output provided.

These WRC water safety planning tools were successfully presented to the international water safety planning community at the inaugural IWA Water Safety Planning

Conference in Kuching, Borneo in 2010. In particular, it was noted that web-based reporting systems and automatically generated risk assessment reports offer cost saving, time saving, reliability advantages and the potential for enhanced management oversight. Furthermore, the value and importance of the inclusion of a similar tool for wastewater aspects was highlighted by municipal officials and sector stakeholders.

Wastewater risk abatement planning tools

With the release of the DWS Green Drop Certification 2012 requirements, the Department extended the risk-assessment based regulatory approach into the sanitation arena. Indeed, the Wastewater Risk Abatement Plan (commonly referred to as W$_2$RAP) borrowed from the water safety planning approach (used for drinking-water quality risk assessments) and is the primary tool with which the sector would assess and monitor the performance of wastewater treatment services at water services institutions (WSIs). In a similar fashion to the WRC's support for WSPs, when municipalities reported challenges with the development and implementation of W$_2$RAP, WRC again responded to the request for support through funding the development of a W$_2$RAP guideline. Indeed, WRC recognised that an opportunity existed to both extend the principles and approach outlined in the W$_2$RAP guideline document and learn from the success of the WSP process to create both spreadsheet- and web-based tools that could be used by the sector to assist with W$_2$RAP development and implementation. A key benefit of the project approach was also the development of a national database of wastewater hazardous events, and therefore WSIs have access to a supported database where their peers and dedicated professionals share common experiences and challenges, resulting in a more appropriate, and therefore more widely accepted and used, tool.

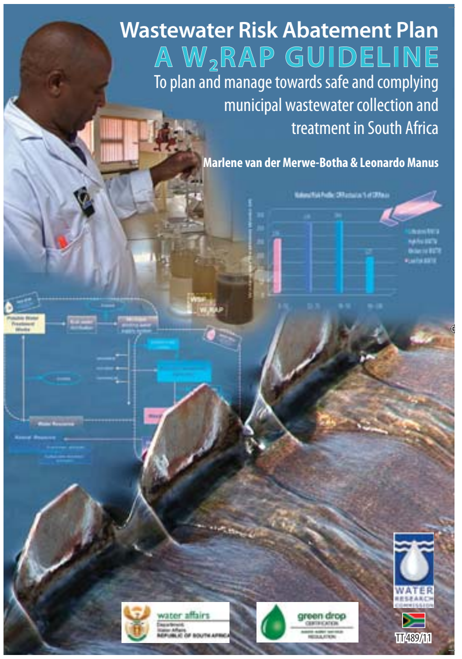


Figure 18. The W2RAP guideline for water service authorities.

Emanti Management, having been involved in WRC's WSP support efforts, were fortunate to be involved once more in developing the Wastewater Risk Abatement Plan Tool (web-based and supportive spreadsheet-based tools, and supports the development and tracking of a W$_2$RAP) and the associated Wastewater Risk Abatement Planning Status Checklist Tool (web-based and supportive spreadsheet-based tools, and supports the user to determine status of W$_2$RAP processes - i.e. Where are we? What have we completed? What must we still do?). Importantly, the W$_2$RAP Tool not only supports the assessment of the formalised wastewater systems (i.e. off-site sanitation – with collection, pump stations, sewer lines and wastewater treatment works), but also includes consideration of sludge management and disposal, non-reticulated systems/on-site sanitation, and the receiving environment and end users. These tools provide municipalities and the private sector with a basis to effectively manage and mitigate both their water supply and sanitation systems risks.

Capacity building for improved water and sanitation services risk management by municipalities

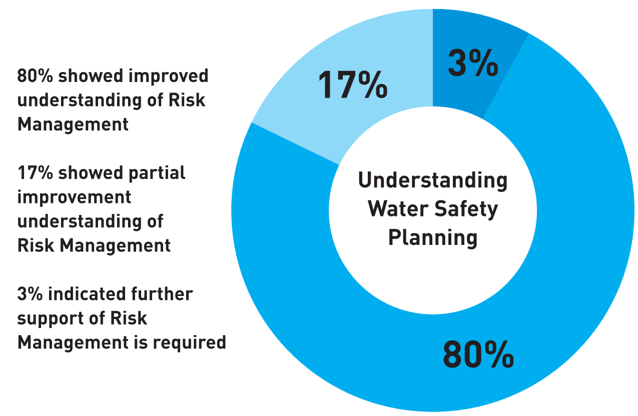
The WRC and the national Department of Science and Technology then investigated the need for capacity development and support in terms of effective and practical implementation of risk management and risk mitigation. As a result, Emanti Management were tasked by WRC and DST to:

- Assist in the assessment of current WSP and W_2RAP processes at identified District Municipalities in the Eastern Cape and KwaZulu-Natal.
- Provide guidance and technical support within existing risk management structures to allow continuous improvement.
- Assist in the development of new risk management for both water and wastewater at challenged District Municipalities.
- Capacitate municipal officials to improve their risk management through supportive development and implementation of WSPs and W_2RAPs
- Provide a platform for the increased use of WRC WSPs and W_2RAP tools

Outcomes were as follows:

- WSPs and W_2RAPs were assessed in terms of vulnerability for the 12 selected WSAs.
- Improvement Plans were completed for 11 of the 12 selected WSAs.
- Full WSP and W_2RAP processes were undertaken at 13 systems within the municipalities of Amajuba, Zululand, Uthungulu, Uthukela, OR Tambo and Ugu.
- 212 persons received risk management based technical support and capacity building.
- Capacity building was also facilitated within 3 sector conferences/workshops including (1) 2016 WISA Conference, (2) 2016 National Human Settlements Conference, and (3) 2016 National Research Foundation/ South African Agency for Science and Technology Agent Workshop.
- Three World Wide Fund for Nature (WWF) interns and one DWS intern was capacitated through the implementation of the project.

Based on a survey of the targeted municipalities, the following valuable improvements and benefits arising from the WRC/ DST intervention can be noted. Whilst improvements were considerable as regards both drinking-water and wastewater, it is clear that further support is necessary in the wastewater arena.



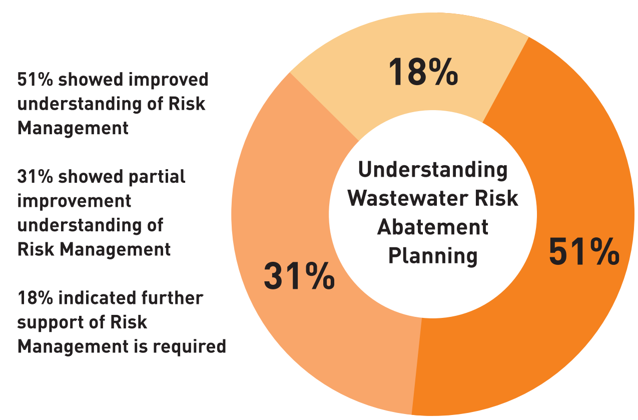


Figure 19. Improved Understanding of Water Service Planning and Wastewater Risk Abatement Planning.

Climate variability and change: Building municipal resilience through practical risk management

It is well known that South Africa is amid a long-term water crisis, with recent droughts experienced in the Western Cape and recent floods experienced in KwaZulu-Natal making it particularly challenging for municipalities and water utilities to reliably deliver sustainable drinking water and sanitation/ wastewater services. These institutions, however, struggle to interpret and incorporate climate data/information into their risk management and planning activities. Given the urgency of climate change impacts to South Africa, the WRC found it an ideal opportunity to develop and implement an easy-to-use and robust methodology that can empower these institutions to take the necessary first steps to build climate resilience.

A WRC project entitled ***Using climate data to help South African water services institutions improve water safety and wastewater risk abatement planning and enhance resiliency to climate change at local and catchment level*** was launched in 2020. The project has enhanced local understanding of resilience and water security and will help to ensure that these institutions continue to provide reliable, safe, and affordable services now and into the future. The approach allows early detection/warning of possible areas of concern, leading to improved planning for disasters, reducing response time/downtime, improving protection of water and wastewater systems related infrastructure, and ultimately improving both public and environmental health.

Understanding broad municipal sanitation system risks

In addition to managing waterborne sewage via wastewater treatment works, and harnessing the aforementioned methodologies aligned with the Green Drop, South Africa also needs to recognise and manage the risks associated with on-site sanitation systems (such as pit latrines) and even those communities driven to open defecation. In this regard, the Shit Flow Diagram (SFD), unashamedly so called by such notables as Bill Gates and President Modi of India, is a handy tool that summarises via an easy-to-interpret colourful diagram the risk / safety profiles of management of human excreta in a community, municipality, or city. As shown below, the SFD is therefore a powerful advocacy tool to engage political, financial and technical decision makers within the planning, financing and management of sanitation services provision.

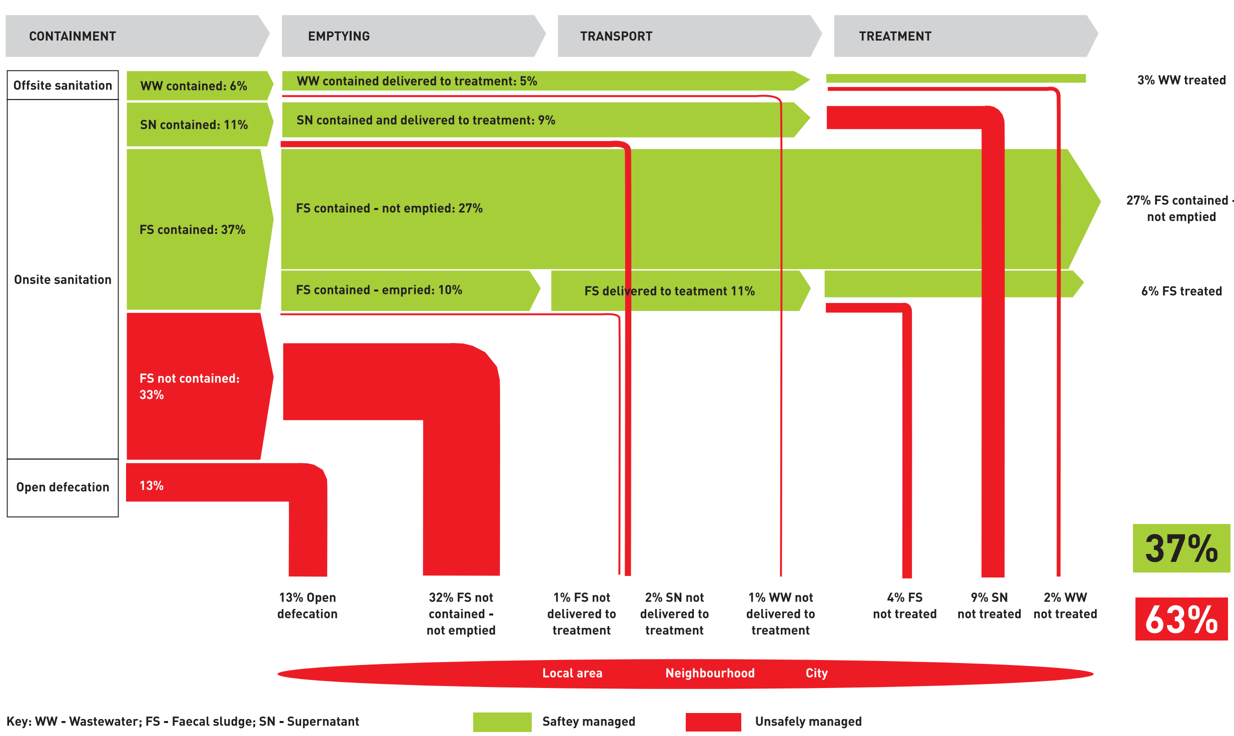


Figure 20. An example of an SFD graphic clearly showing that 37% of the sanitation supply chain is safely managed and 63% in unsafely managed with open defecation taking place.

Importantly, whilst the SFD output is a simple and powerful visual summary, the underlying methodology is comprehensive in its assessment as to the safety/risk status of human excreta management through the extended sanitation supply chain including storage, collection, transport, treatment and safe end-use or disposal of faecal sludge. The benefit of the SFD tool is that it offers an innovative way to engage relevant stakeholders, including political leaders, sanitation experts, civil society organizations, in a co-ordinated dialogue about excreta management. Therefore, it can assist with both improved understanding and communication of technical issues to non-technical persons and can subsequently be used to support decision-making regarding sanitation planning, operations and maintenance, and associated financing.

Without the necessary information indicating sanitation status (such as a sanitation management plan, including SFDs), the risk of sanitation management failures and associated environmental pollution – including untreated faecal sludge ending up directly in the local environment – is substantially raised. Poorly managed faecal and wastewater sludge (e.g., where it is left to accumulate in inadequately designed pits or discharged into the environment) poses a significant health threat to the public and to the natural environment. By contrast, correct use of sanitation management plans (including SFDs) in managing human waste can substantially assist in improved sanitation services and the associated reduction in health and environmental risks.

Together with the WRC, Emanti Management led the first South African SFD initiative where SFDs were initially piloted at 8 volunteer municipalities around the country. Learnings were fast tracked via inputs and guidance from the Centre for Science and the Environment (CSE) of India. Peer-based Master Class sessions have been hosted and the methodology has been promoted by Emanti and WRC to the sector, including the National Sanitation Task Team. During these municipal interaction processes, a number of South-African-specific innovations have been developed and introduced to make SFDs more appropriate for South African conditions. These include an SFD-based Sanitation Priority Improvement Plan which notes that identifying your municipal SFD status is only the advocacy starting point for improvements. Sanitation Priority Improvement Plans are intended to:

- Close the gaps
- Develop a remedial action plan and
- Implement the remedial action plan

Importantly, this process is gathering both local momentum and international alignment with both Emanti and the WRC continuing to support it.

Framework for a risk-based approach for water services asset and infrastructure management

It has long been recognised that asset and infrastructure management is an integral part of water and sanitation services delivery. The need to build capacity for asset management in the South African water services sector was recognised by the WRC soon after the dawn of the new democracy, an era which was marked by the need to expand municipal infrastructure and services to previously unserved areas. By 2001, one of the first WRC guidelines and supporting information and tools on asset management was developed (Stephenson, et al., 2001). In 2005, the WRC, as part of the Global Water Research Coalition (GWRC) supported an initiative to commission a study on the development of a framework and tool for risk management of water utility assets ((GWRC, et al., 2008).

Following this initiative, the WRC subsequently commissioned a study aimed at establishing asset and infrastructure management practices in the water and sanitation services sector (von Holdt, et al., 2009*). This study served as point of reference for South African utilities as they embark on the journey towards the implementation of a risk-based approach for the management of water infrastructure assets. In support of the achievement of the Millennium Development Goals (MDGs), where member states, including South Africa, committed to ensuring sustainable water services provision to all communities by 2015, the WRC initiated a study aimed at determining the vulnerabilities and risks of water services infrastructure and the development of guidelines for supporting municipalities in managing the identified risks (Emanti Management, 2011). Subsequently, these aspects have been incorporated into the Blue and Green Drop programmes.

Building a culture of risk governance in water and sanitation services

The benefits of grounding principles of preventative risk management in water and sanitation services have over the years been manifested in the incremental improvements in municipal performances under the Blue and Green Drop programmes (WINSA, 2015). Globally, the adoption and implementation of a water safety plan approach to ensure the delivery of safe water and sanitation services has hailed as a major step towards risk governance. According to Pollard et al. (2014), risk governance in water and sanitation services provision extends beyond first principles and examines the practicalities of resilience and vulnerability assessment, strategic risk appraisal and the interconnectedness of water utility risks in a networked infrastructure.

Accordingly, the WRC commissioned a nationwide study aimed at developing a comprehensive understanding of how risk is managed and governed in a wide range of water service sector stakeholders, and assessing the level of maturity in risk governance in the sector. As part of this study, the typical risk profile of water utilities, highlighting the many risks that water service institutions have to manage, was developed (Figure 21). Furthermore, a guideline for assisting waster services institutions in implementing risk governance by identifying business value creation benefits and strategic opportunities of integrating risk governance with other business processes was developed (McDonald & Fell, 2016). As a follow-on step, the WRC will be exploring means of incorporating this aspect as part of the current water services regulatory framework.

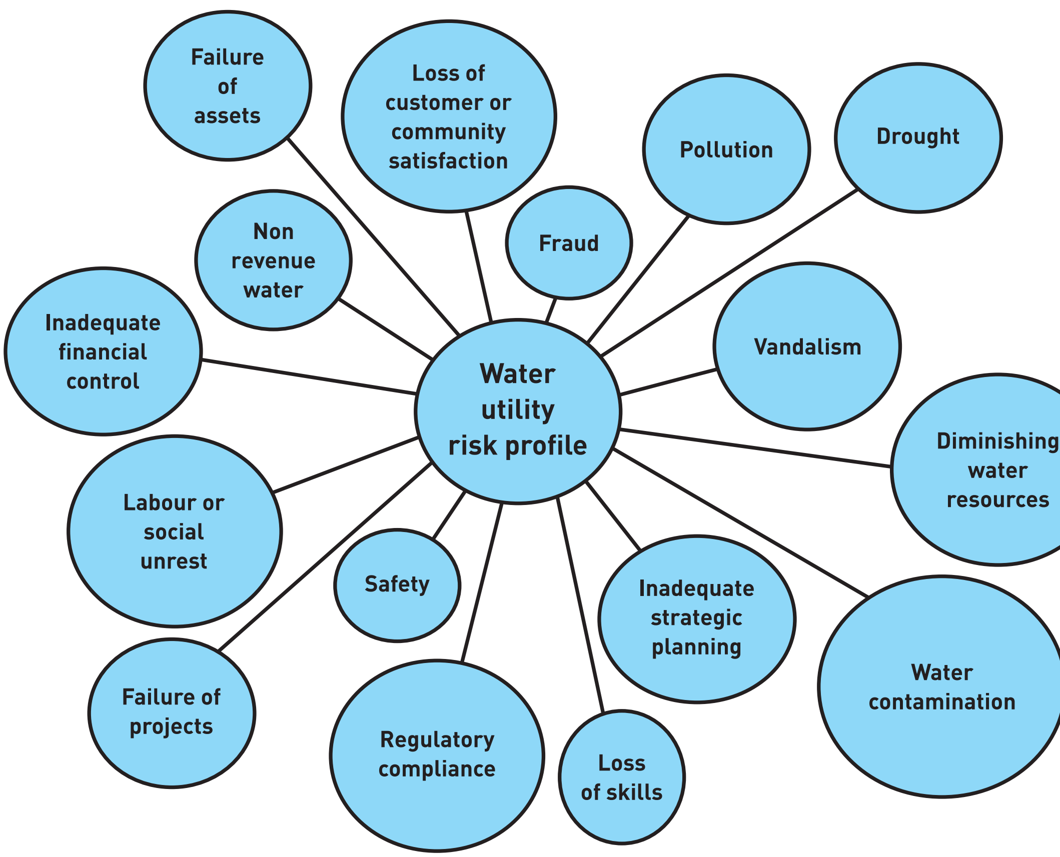


Figure 21: The risks water utilities now face extend beyond the immediate operational environment and may be influenced by regional, national and even international events. Source: McDonald & Fell (2016)

Conclusion

Given the multiple challenges faced by municipalities of South Africa in the water and sanitation services provision space (lack of human resources, limited, proactive maintenance, lack of prioritisation of adequate funds, needs to address service delivery backlogs, etc.), municipalities can benefit considerably by harnessing risk management and governance approaches. The WRC has recognised this and played a significant and meaningful role in supporting both the development and supportive implementation/capacity development of South Africa appropriate risk management approaches – such as Water Safety Planning, Wastewater Risk Abatement Plans, and most recently, SFDs. The development and introduction of appropriate tools to support and guide municipal water and sanitation services practitioners have contributed significantly to ensuring that appropriate water safety planning, wastewater risk abatement planning and ultimately, risk governance are being implemented in South Africa.

In addition to developing and piloting innovative approaches, building capacity, providing guidance and training municipalities, the WRC continues to implement and refine these (and other) risk management and governance tools that municipalities can use to ensure sustainable water and sanitation service provision now and into the future.

Collaborations between the WRC, DWS, SALGA and research partners such as Emanti Management and other universities has provided significant benefit to the South African water and sanitation sector, and Emanti Management has been proud to support the WRC in achieving such.

HUMAN HEALTH: INFECTIOUS DISEASES

Contextualising human health within the WRC framework

Traditionally, studies on water-associated human health have been funded within the WRC Key Service Areas KSA 1 (Water Resources and Ecosystems) and KSA 3 (Water use, wastewater resource and sanitation futures). KSA 1 focuses on resource quality management; water pollution and depletion as they relate to human health; emerging contaminants; risk-based water quality guidelines; and source water protection. KSA 3 focuses on water-sensitive and resilient settlements (rural and urban); water quality futures; sustainable integrated wastewater (transitioning towards a circular economy); and the sanitation transformation initiative (minimising health risk through use of suitable toilets, and re-using limited resources) (WRC, 2021).

The establishment of WRC 'Lighthouses' over the last five years has created a platform for transdisciplinary studies by acknowledging the inter-relationships in the water value-chain. The introduction of these lighthouses brought about a shift in how studies are conceptualised, and has been a positive move towards bridging research gaps. By merging multi-KSA projects under the Water Quality and Health lighthouse, projects on human health and hygiene can now cut across water quality, water services (supply and sanitation) and socio-economic research silos. The paradigm shift in how research is undertaken moves us collectively towards greater inclusivity and collaboration, and ultimately to a better quality of life for South Africans. "In this era of growing uncertainty, addressing water quality challenges requires new imperatives that support a shift to more sustainable, integrated, and equitable approaches." (WRC 2021, p.1).

Overview of WRC-funded human health research in the last 20 years

Over the last two decades, more than 65 studies directly related to human health and infectious diseases have been funded by the WRC. Endocrine disrupting contaminants (EDCs), wastewater treatment, microbial contamination (see ***Water Quality and Pollution*** chapter), oestrogens, community health, health education, health indices, food gardens, sanitation, pesticides, water re-use and potable water, are among the top funded research foci (much of which was conducted together with Department of Water Affairs and Forestry, and the Department of Health). More than a dozen reports have been produced on HIV or HIV-related vulnerability alone. Several reports on disease vectors and water-borne diseases have also been produced since the turn of the century, malaria, bilharzia (schistosomiasis), and liver fluke disease being of particular concern in southern Africa.

Outbreaks of cholera in rural communities drew attention to poor surface water quality caused by faecal contamination of water bodies on which local people rely for everyday life (including social, cultural, and religious practices) (Ntema et al., 2014). In response to these issues, WRC focused on methodologies and technologies that would improve the water treatment process. More recently, the COVID-19 pandemic has shone a global spotlight on South Africa, as resource constraints further intensify the level of threat to livelihoods and health of vulnerable persons and their caregivers – resources that include water. WRC research related to COVID-19 is current and ongoing.

WRC involvement in communicable disease research: special focus on HIV

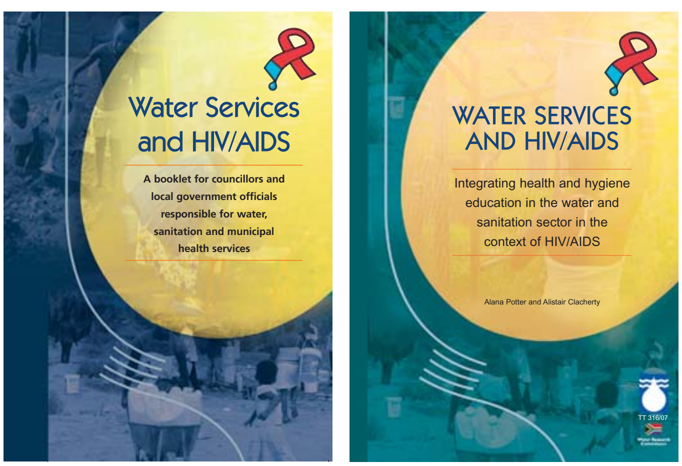


Figure 22. The guidelines developed on water services and HIV/AIDS, published in 2007.

From several isolated cases in the 1980s, to what is now considered an epidemic, HIV/AIDS has had a monumental impact on the lives of South Africans in the last 20 years (Simelela et al., 2015). Globally, South Africa has the largest population living with HIV, estimated at 7.7 million individuals in 2018 (Gareta et al., 2021) and comprising 13% of the country's population (Galvin and Masombuke, 2020). The WRCs involvement in HIV-related studies has been consistent since the early 2000s. Studies conducted between 2007 and 2020 have focused on assessing the effects of contaminants in potable water and mitigating the concomitant effects of poor water quality on the health of immuno-compromised persons and their caregivers (e.g. Obi et al., 2007*). The objectives of the earliest studies were to prevent the spread of water-related diseases (such as diarrhoeal diseases), and to determine the extent to which other pathogens affect HIV-positive individuals (especially in rural areas where water quality and water services are lacking) (Obi et al., 2007*).

In later years, the types of studies funded by WRC were focused on preventative strategies. Clacherty and Potter produced a groundbreaking study in 2007* that not only identified institutional complexities in water and environmental health services, but provided models, strategies, and indicators for implementing health and hygiene education within the context of HIV/AIDS. For the next few years, the WRC would continue to fund projects of this nature, exposing the links between education, policy, service delivery, and water quality on households living with HIV, addressing real cross-cutting issues on the ground. One of the major challenges that was identified was that households requiring additional (paid for) water also experienced significant loss of income due to sickness or death from AIDS-related diseases. This called for new policies that would provide free basic water and sanitation services to those households. Further afield, traction was gaining in Africa (e.g. Kngongo and Chunya, 2009), where these same policies were desperately needed to ensure basic water services for persons living with HIV. Galvin and Masombuke (2020) recently examined the state of affairs in South Africa, and found that although NGO stakeholders submitted a proposed policy framework for this 'new' provision, the Department of Water and Sanitation ultimately failed to develop a new policy.

Studies on the risks of poor water quality and sanitation on caregivers (and those reliant on them for home-based care) in rural areas continued between 2007 and 2014 (Obi et al., 2007*; Potgieter and DuPreez, 2012*; Potgieter, 2014*). Further funding was awarded for projects assessing the extent to which poor water filtration affected the most vulnerable individuals (children under the age of 5 and those living with HIV)

(Potgieter et al., 2014*). The role of dysfunctional wastewater treatment works in the accumulation of contaminants was also identified during that time, but another research focus emerging from this would culminate in a major report, to date the most complete assessment of the risks of antiretrovirals (ARVs) in South African water sources (Bouwman et al., 2020*).

A shift in the political landscape in the country saw the prioritisation of antiretroviral (ARV) rollouts in early 2004 (Simelela et al., 2015). Little was known about the pathways of ARVs in freshwater at the time. Screening studies to determine the presence and toxicology of ARVs and other pharmaceuticals were funded to improve public health and the understanding of how trace pharmaceuticals affect healthy and vulnerable persons and communities (Swanepoel et al., 2015). It was only in 2015 that the first report on the effects of ARVs in water, and in fish, in South Africa was published (Swanepoel et al., 2015). More recently, Bouwman et al., (2020*) produced a WRC-funded complete risk assessment of ARVs in water resources, which is the first of its kind after more than a decade since the confirmed presence of the contaminants in household water.

What about COVID-19?

"The Water Research Commission (WRC) on 20 May 2020 launched a special programme on the surveillance of COVID-19 in wastewater. Conceptualised as the implementation vehicle for monitoring the spread of COVID-19 in communities, the primary aim of this programme is to share knowledge, stimulate research and innovations on water quality, sanitation and health and support the initiatives of government in curbing the spread of COVID-19.

WRC 2021

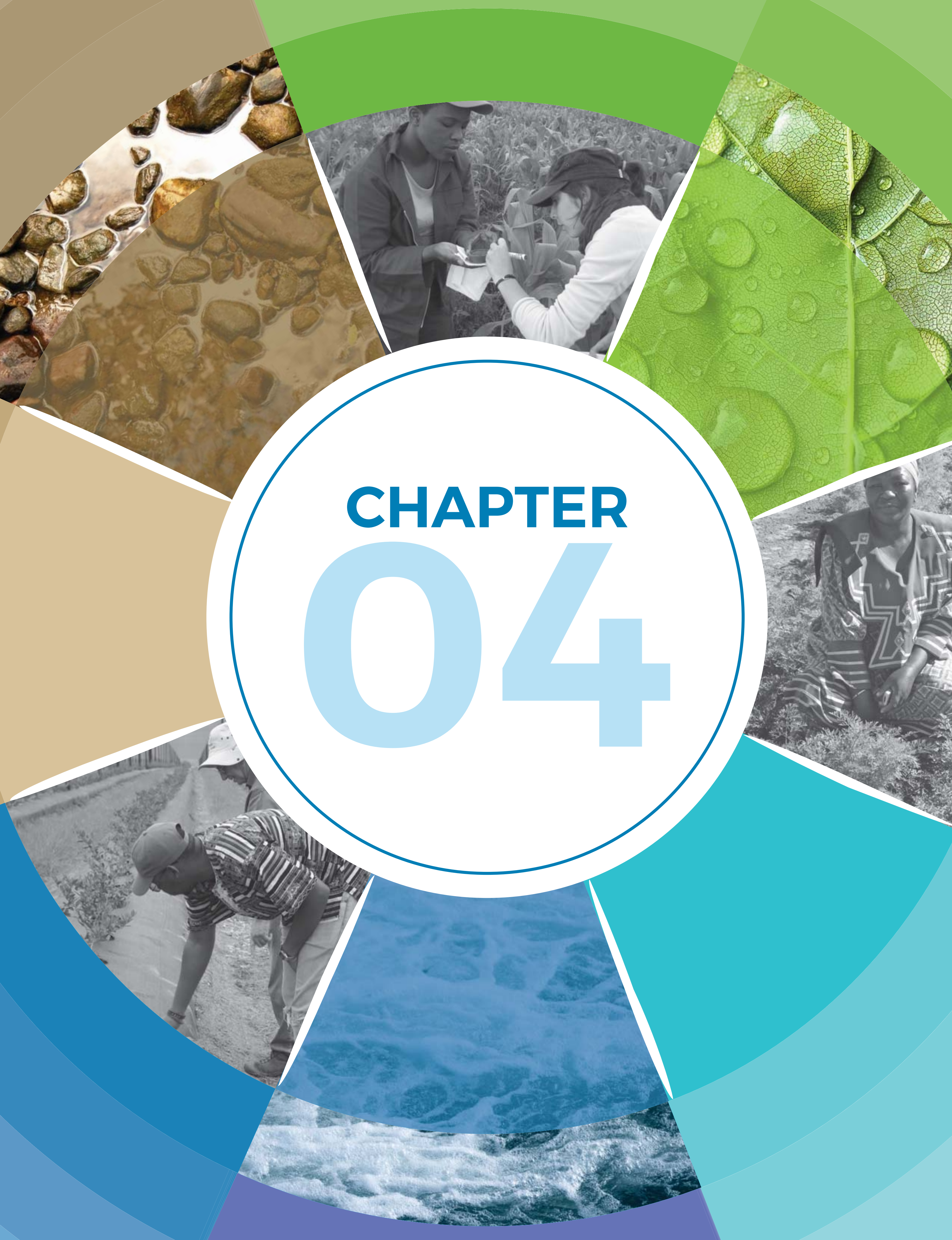
FUTURE RESEARCH

In earlier years when the available water resources were plentiful, high assurance and quality of water supply together with wastewater treatment were the primary areas of attention of the WRC's Key Strategic Area 3 (Water Use, Wastewater Resources and Sanitation Futures key strategic area). Population growth, industrialisation and climate variability have impacted water resources availability and quality, necessitating a new approach to water and sanitation services delivery. This is referred to as 'Embracing One Water and Being Water Positive', and is defined as striking a very sensitive balance between water availability and its exploitation, so that future water consumption always affords some security of supply and quality.

Considering the challenges, the future focus of research will be on greater innovation and the development of cutting-edge technologies to respond to the issues of poor operation and maintenance of water and wastewater treatment works, competency and capacity constraints, direct water reuse, energy efficiency, climate change, and emerging contaminants in drinking water. Therefore, the future intent of the portfolio 'Embracing One Water and being Water Positive' will be to address behaviour and practice within this sector. The purpose of this strategy together with the WRC's research, development and innovation (RDI) strategy will be to formulate a new focus for moving forward, as well as to look at multidisciplinary responses and at the integration of the WRC's activities in research and development.

This focus will give effect to the new WRC's key strategic areas of Water Use, Wastewater Resources and Sanitation Futures, to embrace and lead to solutions towards one water and being water positive. The objective is to see all forms of water and wastewater as a resource which will encourage reuse, recycling and recovery technologies and will support the municipal, mining, and industrial sectors. Improved management in these sectors will aim to improve productivity and support economic growth while minimising the negative effects of economic development on human and environmental health. The approach will seek to drive a paradigm shift from end-of-pipe treatment to resource recovery underpinned by innovation.

The WRC should also continue (if not strengthen) its funding stream for human health projects. Communicable disease outbreaks continue to rise, directly and indirectly contributing to poor water quality and increased vulnerability of rural and urban communities in South Africa. What is really needed is policy action supported by transdisciplinary research. The introduction of the WRC lighthouses and the new mega-project format can be effective in dealing with public health crises in so far as they relate to water.



CHAPTER 04

ENHANCING FOOD AND WATER SECURITY THROUGH INNOVATIONS IN SOUTH AFRICA: 50 YEARS OF RESEARCH

Samkelisiwe Hlophe-Ginindza, Vimbayi GP Chimonyo, Luxon Nhamo, Sylvester Mpandeli, Stanley Liphadzi, Dhesigen Naidoo, Albert T Modi and Tafadzwanashe Mabhaudhi

INTRODUCTION

Food and nutrition security remains a global challenge, and South Africa is no exception. Although South Africa is food secure at the national level, it is faced with extreme poverty and food insecurity at the household level. Indeed, South African Statistics reports that one out of four households is food insecure (StatsSA, 2019). Factors contributing to this food insecurity include socio-ecological challenges, climate variability and change, land degradation and inappropriate agricultural practices. The Water Research Commission (WRC) has been at the forefront of developing effective, holistic, climate-smart solutions and innovations to ensure food security through increasing irrigation productivity. Irrigated agriculture remains one of the most important means of meeting national food and nutrition security, supporting 25-30% of South Africa's agricultural production (Nhamo et al., 2019).

This chapter highlights the work funded by the WRC that addresses the challenges of food and water insecurity. Water and food, together with energy, remain the most important resources for human welfare, and their security is vital for achieving the Sustainable Development Goals (SDGs) (Mensah and Ricart Casadevall, 2019). These resources are at the heart of SDGs. Their scarcity in the advent of climate change and impacts on other sectors contributed to the formulation of the SDGs in 2015 by United Nations members (UNGA, 2015). Considerable adaptation through transformational change and innovation is urgently needed in the water and food sectors to ensure uninterrupted supply and efficient utilisation to meet the demands of a growing population (Nhamo et al., 2019). However, the already evident impacts of climate change are additional stressors on food and water resources (Nhemachena et al., 2020). The challenge is compounded by the increasing food and water demands from a rapidly growing and progressively wealthier population (FAO-IFAD-UNICEF-WFP-WHO, 2018). Continued developments in agriculture and its intensification and extensification have dire consequences on land and water resources and natural ecosystems (Allen and Prosperi, 2016). Coupled with urbanisation and increased population growth, the demand for food and water resources is compounding the degradation of ecosystems. This situation is undermining the food-producing systems and aggravating the challenges of water and food insecurity.

Current socio-ecological changes, compounded by climate change, call for viable and effective adaptation strategies through innovation that provides climate-smart solutions to achieve sustainability by 2030 (UNGA, 2015). These climate-smart innovations should be developed to enhance adaptation and resilience to the impacts of the prevailing socio-ecological changes, particularly in the water and agriculture sectors. This requires a sound understanding of the linkages between agronomic practices and agricultural water management. Food and water security remain a universal challenge, with several countries facing the double burden of hunger and undernutrition simultaneously with overweight and obesity (IFPRI, 2016). A third of the global population is presently suffering from malnutrition or water scarcity (IFPRI, 2016). Indeed, it is common to find individuals with different forms of malnutrition living side-by-side. Approximately 800 million people globally face hunger daily. More than two billion people lack vital micronutrients (such as iron, zinc, vitamin A) (IFPRI, 2016), adversely affecting their health, development, and life expectancy. Nearly a quarter of children aged five and under are stunted, with reduced physical and mental capacities. Less than a third of infants in low- and middle-income countries adequately meet the minimum dietary diversity standards required for growth (IFPRI, 2016).

The state of food and water security in South Africa

South Africa is food secure at the national level; however, it is faced with extreme poverty and high-income inequality and approximately 56% of the population lives in poverty (StatsSA, 2019). Many households are faced with food insecurity daily (Chakona and Shackleton, 2019). Most people facing food and nutritional insecurity live in rural areas and informal settlements. StatsSA (2019) stated that approximately 25.2 % of the population lived below the poverty line of R14.70 per person per day (StatsSA, 2019). Rainfed agriculture is the third-most important means of livelihoods, after remittances and Government grants, but it contributes only 10% to household survival (StatsSA, 2019). Given the political and human rights challenges of hunger and unemployment that the COVID-19 pandemic has exacerbated, there is an urgency to provide practical, cost-effective support to smallholder farmers that can be implemented in different agroecological zones.

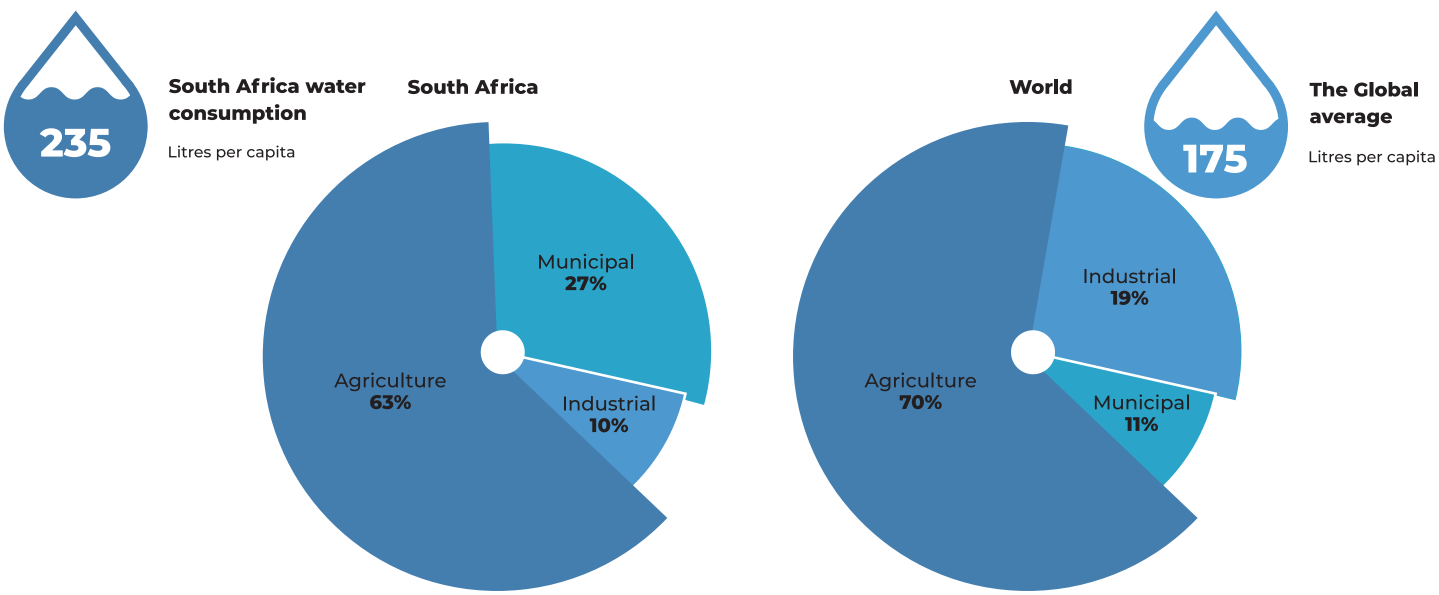


Figure 1. Total water withdrawals in South Africa versus the world by sector. Source: World Bank Indicators.

Agriculture alone uses approximately 9.7 km^3 (about 63%) of the total annual water withdrawals in South Africa (Donnenfeld et al., 2018) (Figure 1). There is an urgent need to enhance water-use efficiency, promote sustainable food systems through circular modelling and improve water productivity, particularly in the agriculture sector. Agriculture is the largest consumer of water in South Africa. Adopting agricultural water management technologies and innovations is critical, as 98% of the country's water resources are already allocated. The situation is worsened by the low average annual rainfall of about 450 mm, which is well below the world average of 860 mm (Davis and Vincent, 2017).

South Africa is the thirtieth driest country in the world, and the situation is exacerbated by multiple drivers such as population growth, migration, urbanisation, ageing infrastructure, expansion of irrigated areas, and increasing frequency and intensity of drought events

(Davis and Vincent, 2017; Matchaya et al., 2019). These drivers of change urgently require transformative and polycentric approaches to address the multiple challenges and ensure water security (Nhamo et al., 2020a).

The WRC has spearheaded research into agricultural water management in South Africa, coming up with innovations that enhance food and water security. The Water Utilisation in Agriculture Key Strategic Area (KSA) or KSA 4 of the Research and Development Branch of the WRC has been at the forefront of these innovations that bring transformational change in the water and agriculture sectors. This chapter is divided into two sections: the first explores the emerging research in water utilisation in agriculture. This section maps out key thematic areas from scientific reports within KSA 4. The focus is to showcase the key research initiatives that have emerged as forerunners within Water Utilisation in Agriculture (in the past 20 years). The second section highlights the key research outcomes within the KSA 4 portfolio, and assesses the current progress, challenges, and opportunities to achieve smart technologies that enhance resource use efficiency, focusing on water and agriculture. These goals were achieved by (i) exploring the emerging research focus under the KSA 4 portfolio and (ii) evaluating the progress towards the realisation of the KSA's objectives. The database used to extract this information consists of scientific reports found of the WRC knowledge hub.

Phase 1: Exploring the emerging research focus under Water Utilisation in Agriculture

In this phase, we assessed the thematic research areas emerging from the scientific reports submitted under KSA 4. Firstly, a word cloud was generated from keywords identified in report titles. A word cloud is a special visualisation of text in which the more frequently used words are effectively highlighted by occupying more prominence in the representation. The more often the word appears within the passage being analysed, the larger it appears in the image generated. This provides viewers with a synopsis of the main themes contained within the text. Word clouds are increasingly being used within the public and private sector as a tool to identify the focus of written material. As research tools, however, word clouds have several limitations. They fail to group words with the same or similar meaning, such as 'water use' and 'water utilisation'. In addition, the words were retrieved out of context as the technique omits the semantics and phrases they comprise.

We performed a bibliometric analysis to establish the main trends within the identified key terms to overcome this limitation. Bibliometric analysis is a quantitative method to assess published papers and has become helpful to evaluate studies in a specific field of research (in our case, Water Utilisation in Agriculture (scientific reports) (Rey-Martí et al., 2016; Small, 1973). The bibliometric analysis examines secondary data acquired on a digital database from a quantitative and objective perspective (Albort-Morant and Ribeiro-Soriano, 2016). Also, such analysis can help to structure the evolution of a focal research area (Cobo et al., 2011; Klavans and Boyack, 2006). For the second part of this phase, we used VOSviewer software as a tool to map associations within the key term analysis obtained from titles of reports submitted under Water Utilisation in Agriculture.

Phase 2: Evaluating the progress toward achieving the realisation of KSA 4 objectives

During the second phase, we relied mainly on the outcomes of KSA 4 thrust and programmes to assess the current progress, challenges, and opportunities to achieving the primary objective of KSA 4, which is "To increase national and household food security and to improve the livelihoods of people on a farming, community and regional level through efficient and sustainable utilisation and development of water resources in agriculture". Therefore, the synthesis of the literature was structured around the thrusts and programmes falling under KSA 4 (Table 1).

Table 1. Current thrusts and programme of the WRC Water Utilisation in Agriculture Key Strategic Area.

THRUST 1: WATER UTILISATION FOR FOOD, FORAGE AND FIBRE PRODUCTION	**Programme 1:** Water-efficient production methods in relation to soils, crops and technology in rain-fed and irrigated agriculture
THRUST 2: WATER UTILISATION FOR FUELWOOD AND TIMBER PRODUCTION	**Programme 1:** Water-efficient production methods and systems in agro-forestry, woodlands and forestry plantations
THRUST 3: WATER UTILISATION FOR POVERTY REDUCTION AND WEALTH CREATION IN AGRICULTURE	**Programme 1:** Sustainable water-based agricultural activities in rural communities
	Programme 2: Integrated water management for profitable farming systems
THRUST 4: WATER RESOURCE PROTECTION, RESTORATION AND RECLAMATION IN AGRICULTURE	**Programme 1:** Sustainable water resource use on irrigation schemes and within river catchments.
	Programme 2: Impact assessment and environmental management of agricultural

Exploring the research focus trend of the WRC

Research characteristics

KSA 4 thrusts and programmes within the WRC strive to balance projects on irrigated and rain-fed agriculture, agro-forestry, and aquaculture, to promote farmer involvement in poor rural communities through participatory action research, and to progress research projects further toward the practical application of results with technology transfer activities. A large proportion of projects funded under the Water Utilisation in Agriculture portfolio fell under Thrust 3 (Figure 2), which has a strategic focus to improve the management processes undertaken by people using water in agriculture.

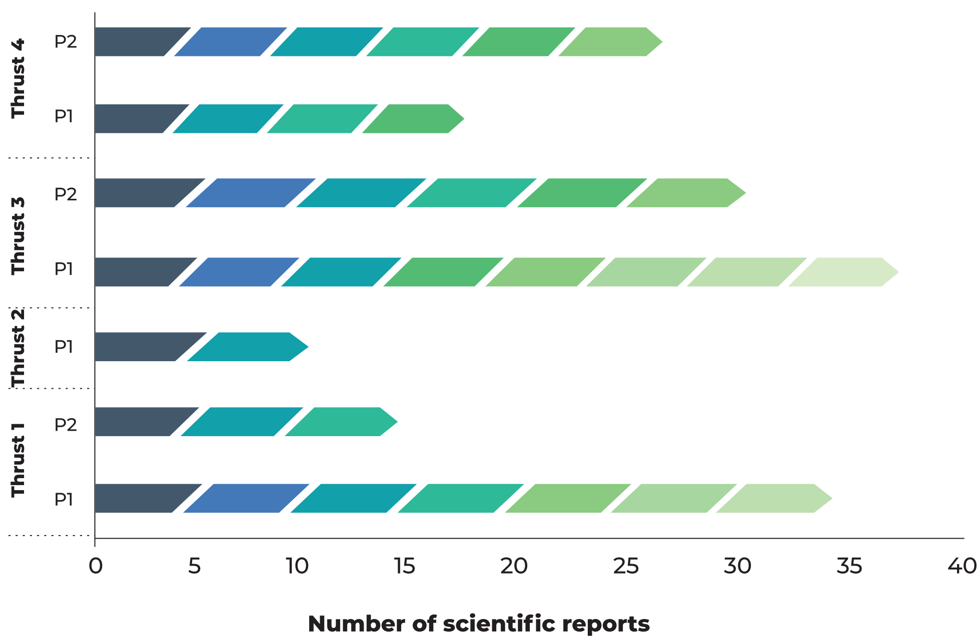


Figure 2. Scientific reports under the different Thrusts and Programmes (P) in KSA 4 for the period between 2001 and 2021.

The most funding has been granted to research on sustainable pathways to address poverty, hunger, and malnutrition among rural communities. However, research on water utilisation for fuelwood and timber production (Thrust 2) remains low, with the smallest number of funded projects.

Water use in the irrigation sub-sector

Within South Africa, irrigated agriculture remains one of the most important means of meeting national food and nutrition security. Irrigation stabilises food production as it protects against the unpredictability of rainfall. Irrigation supports 25-30% of our national agricultural production. It is estimated that irrigation is responsible for up to 90% of the production of high-value crops (including potatoes, vegetables, and fruit) and 25-40% of the production of industrial crops (including sugarcane and cotton). Since its inception in 1971, the WRC has always understood a need to improve overall irrigation efficiency for sustained water, food, and nutrition security. Within the context of irrigation and irrigation efficiency, research within the WRC has been extensive, covering management, appropriateness of developed technologies, economics, and sustainability.

Figure 3. Irrigation supports 25-30% of South Africa's national agricultural production.

For instance, Reinders (2010*) suggested that irrigation efficiency be assessed from the source to the root zone (Reinders, 2010*). Oosthuizen (2005*), Volschenk (2005*) and Reinders (2012*) assessed the cost-effectiveness of large- and small-scale irrigation systems. Several irrigation technologies have also been evaluated (Reinders 2004*). Other studies have applied models and measurement tools for evaluating water flow (Hlela-Mwanyama, 2004*) and the performance of filters (Volschenk, 2006*). Decision support tools, such as OPERA (de Clercq, 2019*), SAPWAT (van Heerden, 2008*; van Heerden 2020*), PLANWAT (van Heerden, 2008*), and FARMS (Volschenk, 2005*) have been proposed, while (Singels, 2008*) offered a tool which offers real-time advice to farmers in issues on irrigation water management. The projects further developed and tested models that determined the economic effectiveness of water rationing in irrigation systems (Pott, 2012*).

From the water quality point of view, WRC-funded research has considered issues regarding the use of various types of mine water such as gypsiferous (Beukes, 2006*) and the impacts of salinity (du Preez, 2012*), microbial contaminants (Sigge, 2016*; Moyo et al., 2020*) and heavy metals (Moyo et al., 2020*) on water quality and its fitness for use in agricultural production. The impact of reduced water quality on crop growth, water use, and food quality (Britz, 2013*) have also been explored. The 1996 ***South African Water Quality Guidelines for Irrigation*** (Annandale, 2017*) and the ***South African Irrigation Design Manual and Irrigation User Manual*** (Dhavu, 2020*) were reviewed and updated to suit the current environment. Everson (2012*) produced the support material through a project aimed at farmers using irrigation systems for pasture production. Of note is the attempt to address the effects of droughts and floods by exploring the latest irrigation management strategies (le Roux, 2021*).

Smallholder irrigation schemes

Smallholder irrigation schemes constitute 3.3% of the total irrigated area (1.5 million ha) in South Africa. The current role envisaged is that they create employment and reduce poverty, particularly among rural women farmers in South Africa. Unfortunately, many smallholder irrigation schemes have collapsed while the rest are suffering reduced efficiency for various reasons. These include incorrect water allocation, poor leadership among elected representatives, lack of understanding of governance issues etc. Nevertheless, due to the importance magnitude and relevance of these schemes, their effective revitalisation is extremely important.

Figure 4. Examples of the different irrigation aspects covered through WRC-funded research.

According to Van Averbeke et al. (2011*), the WRC made its first enquiry into smallholder irrigation schemes in 1985, more than ten years after its establishment. Legoupil (1985*) concluded that: smallholder irrigation failed to provide high yields due to a myriad of technical, management, training, agricultural policy, and financing issues. It was only in the late 1990s and early 2000s that research around smallholder irrigation schemes, and the need to revitalise them, took centre stage [see De Lange (1994*), IPTRID (2000), Du Plessis et al. (2002*), Shah et al. (2002*) and Backeberg (2006).

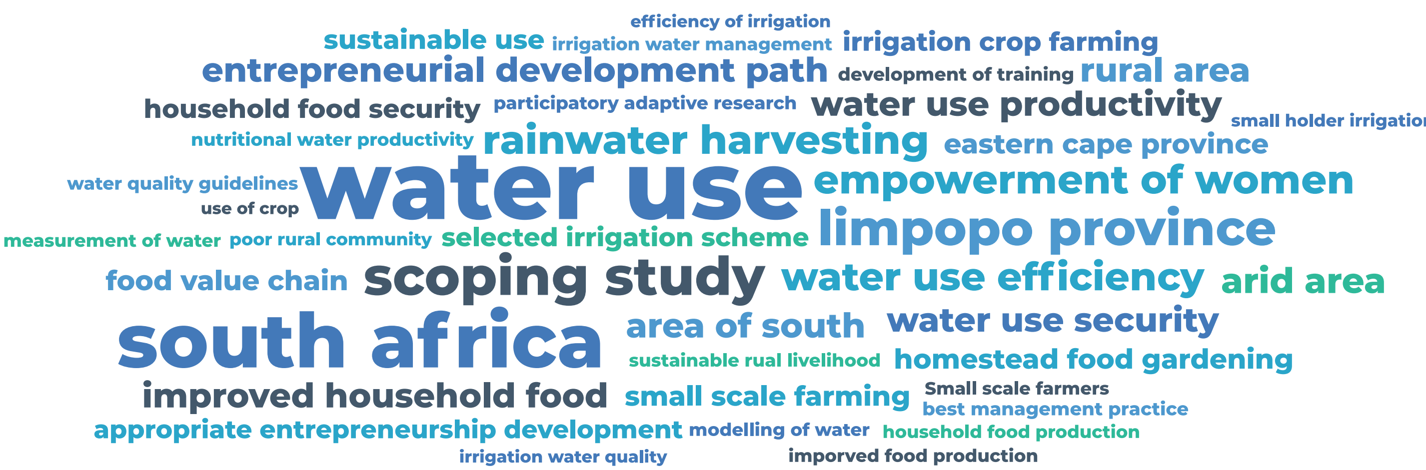


Figure 5. Key terms identified in scientific report titles submitted under KSA 4 (Water Utilisation in Agriculture).

For nearly 20 years, smallholder irrigation schemes have been one of the focal points of agricultural water research initiated, funded, and managed by the WRC. The vast number of projects focusing on revitalising irrigation schemes demonstrates that the WRC is at the forefront and centre in these efforts. Projects that focused on smallholder irrigation schemes have been conducted against the backdrop of the need to tackle issues of rural poverty, unemployment and increase food and nutrition security in former homelands situated in Eastern Cape (Obi, 2016*), Limpopo (Denison, 2016*) and KwaZulu-Natal provinces (Zegeye, 2018*). Denison (2007*) considered 317 schemes which revealed that the weaknesses of prior efforts to revitalise them included limited consultation and engagement with the intended beneficiary and human and social capital.

Some projects funded by the WRC have mapped empowerment and development pathways associated with water productivity and security within smallholder schemes to shift to commercial-based crop production. Exploratory studies were used to determine the potential and opportunities of irrigation schemes within historically disadvantaged communities (Hlela-Mwanyama, 2004*; Jiyane, 2019*). In addition, farm-ownership models used in establishing the farms were evaluated. The projects mentioned above played a major role in empowering and improving the livelihoods of previously disadvantaged communities and smallholder farmers.

Aquaculture

Freshwater aquaculture can contribute to economic development and food security in rural areas of South Africa. Water is recirculated within the systems, which partly addresses the problem of water scarcity. According to Rouhani and Britz (2004*), during the early 1980s, several fish hatcheries and production units were set up in the former homelands (Gazankulu, Ciskei, Transkei, and Venda) to contribute to food security. However, by the 1990s, all of these had failed. The collapse was due to a lack of extension services, financial support, and political will. The WRC, recognising the potential of aquaculture for water, food, and nutritional security, assisted in identifying key research priority areas. One research area that has become prominent in aquaculture is water quality. The interaction between agriculture and aquaculture has been explored by monitoring the water quality of on-farm dams (Salie, 2008*; Salie, 2013*; Salie, 2017*). In addition, livestock production was singled out in these assessments, and a risk-based approach for assessing livestock watering guidelines and aquaculture water quality guidelines was adopted (Moodley, 2021*). A smartphone application was also recently developed (Rouhani, 2021*) to convey a revised WRC manual on aquaculture to small-scale farmers through a digital platform.

Water security and empowerment

In South Africa, social protection, water, and gender have become topical, especially within social justice and equity discourse. It has long been established that water insecurity restricts female participation in social protection (and related education and employment opportunities) and undermines efforts to promote health, nutrition, and food security (Mudhara, 2020*). The WRC has supported gender-sensitive improvements in water security by enhancing and empowering women's access to water (Denison, 2015*; Chitja, 2015*; Oladele, 2016*, Figure 1 and 2). Additionally, projects funded by the WRC have focused on increasing the capacity of marginalised communities to manage market- (van Schalkwyk, 2007*) and water-related (Korsten, 2016*) risks. Overall, water security and empowerment projects have focused on water use, entrepreneurial development, and sustainable water use. In addition to women, targeted groups for water security and empowerment studies have been rural communities (Asiwe, 2020*) and smallholder farmers (Zegeye, 2018*).

Improving water productivity for increasing food security

Food and nutrient security have been at the forefront of most WRC-funded research studies, and water availability is the limiting factor in most arid regions. Studies that focused on improving food security examined a case study (Chitja, 2015*; Denison, 2015*) and scoping review approach (Wenhold, 2012*). The studies were conducted to empower vulnerable groups, particularly women (Chitja, 2015*; Mudhara, 2020*), small-scale farmers (Lotz-Sisitka, 2021*), and the study sites were in Limpopo, Eastern Cape, and KwaZulu-Natal provinces (Chitja, 2015* and Denison, 2015*) except for the scoping review that focused on South Africa in general (Wenhold, 2012*).

The investigation into existing and new 'food value chains' has also been central in addressing the need for improved water, food and nutritional security among disadvantaged groups and emerging farmers (de Lange, 2014*; Letty, 2014*). The projects that researched food security suggested that investigations should develop small economic players into the mainstream economy, starting from the grassroots level (Chitja, 2020*). Homestead food gardening has been responsible for subsistence food security with no option of generating income for the household.

Crops that were considered in water-use efficiency and crop water productivity projects included indigenous tree and crop species (Dye, 2008*; Oelofse, 2008*; Everson, 2016*, Modi, 2013*, 2017*, Modi and Mabhaudhi, 2020*), fruit trees such as apples, pomegranates, avocado and macadamia (Bush, 2014*; Dzikiti, 2018*; Volschenk, 2019*; Taylor, 2021*), crops and trees for biofuels (Jewitt, 2009*), vegetables (Korsten, 2015*), and pastures (Truter, 2016*). The projects investigated the interaction between water use and biomass (Dye, 2008*; Gush, 2014*), value chains (Grove, 2012*) and crop nutrient content (Wenhold, 2012*). Attempts have been made to measure water use in pomegranate orchards (Volschenk, 2019*), trees that have multiple uses (Everson, 2019*), and apple orchards (Dzikiti, 2018*). Water use has also been investigated through research that seeks to address mitigation and adaptation to climate change to ensure sustainability (Modi, 2013*; Ncube, 2017*). Water use has been used to highlight the potential to alleviate poverty among disadvantaged groups through realising gender equity, capacity building and entrepreneurial development.

Discussion and way forward

The challenge of improving resource security is not linear nor monocentric but multi-faceted and polycentric, requiring integrated and circular modelling through transformative approaches such as nexus planning, the circular economy, sustainable food systems, and scenario planning (Nhamo et al., 2020a). Figure 6 illustrates the four thematic areas required to comprehend the complex socio-climatic and environmental interactions and the drivers of change in the context of nexus planning to ensure the security of water, energy, and food resources (Allen and Prosperi, 2016*). The thematic areas include (a) drivers of change, (b) risk and exposure, (c) nexus planning and (d) water and food security. The framework also illustrates the pathways towards efficient agricultural water management solutions and sustainable food systems that ensure human health and environmental integrity. Water insecurity is driven by socio-economic and environmental changes, which increase the vulnerability of communities and risk to human health (Allen and Prosperi, 2016*). Using analytical tools, nexus planning guides strategies for adapting to climate change, and identifies areas for priority intervention. This ensures resource-use efficiency, promotes climate-smart agriculture and improved water productivity, and ensures water and food security (Nhamo et al., 2020a). Thus, transformative approaches encompass low consumption of energy, low pollutant emission and high efficiency in resource use, are restorative and regenerative, and reduce losses in the whole value chain. Transformative approaches are important for breaking the vicious socio-ecological and environmental risk cycle (Lehmann, 2018).

These transformative approaches to resource use can free water that has been allocated to agriculture, to other sectors. The level and rate of the adoption of agricultural water management technologies in both the smallholder and commercial sub-sectors, particularly away from irrigation, are dependent on improving crop water productivity. Freeing more water from the agriculture sector would avail the precious resource to other sectors where it is also needed to drive the economy. Technological developments in the agriculture and water sectors are always important pathways towards sustainability, food and water security, and balanced resource management and development (Cosgrove and Loucks, 2015). Hydrological and water management tools and models particularly, have emerged as essential components of water management. Other technological developments include smart plants that are more drought-tolerant due to genetic modification and genome editings well as plants that have been engineered to use more efficient photosynthetic pathways to fully harness the sun's available energy (Tripathi et al., 2019). These developments hold promise in the arid conditions of most of South Africa.

Some of the interventions that can be used to free water for use in other sectors include:

- Improving crop water productivity (physical, economic, and nutritional) through:
- increasing the marketable yield of the crop for each unit of water transpired by it,
- reducing field-related outflows (runoff, drainage, seepage, percolation and evaporative loss),
- increasing the effective use of rainfall, stored water, and water of marginal quality.
- Enhancing rainwater harvesting (RWH) technologies.
- Adopting water marketing strategies.
- Addressing water scarcity challenges from a nexus planning perspective.

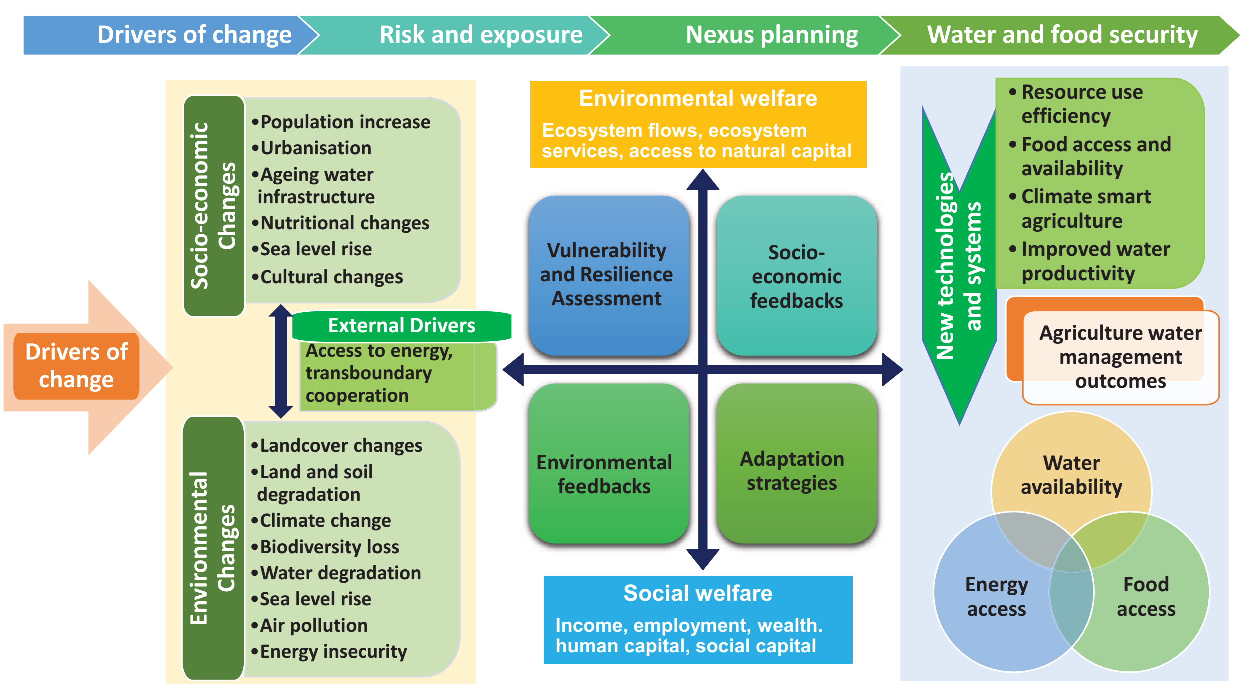


Figure 6. A nexus planning framework illustrating transformational pathways towards improved water-use efficiency, crop productivity and achieving sustainability in the water and food sectors. Source: Liphadzi et al., 2021

Looking into the future

Access to land and water for food production remains a major problem in increasing agricultural activity and ensuring food and nutritional security. In addition, work done by WRC-funded researchers in recent years shows that low entrepreneurial spirit is a key contributor to preventing the establishment of small farming businesses.

The results show that, in order to improve food and water security, there is a need to improve irrigation efficiency, explore different water sources, improve water productivity, and develop new food value chains, including promoting indigenous crops that are more resilient to climate variability and change. Addressing these challenges requires integrated and circular models through transformational approaches, including nexus planning, circular economy sustainable food systems and scenario planning.

Inequalities in income, access to basic services and assets and social exclusion prevent many from benefiting from economic growth. In particular, gender inequalities perpetuate inter-generational poverty and malnutrition. Reducing inequality is thus essential to strengthening household resilience, laying the path to inclusive growth, and reducing food insecurity.

Research is still required to discover the most effective ways of promoting and stimulating economic growth to overcome poverty, hunger, and malnutrition. This will aid in increasing the adoption of water-use efficient technologies that have been developed by the WRC over the years. This may be accelerated through focusing on the demonstration of these technologies to the relevant stakeholders, thus highlighting the 'Moving from Theory to Practice' approach proposed by the WRC.

Addressing food insecurity, building human capital, and strengthening access to, and use of basic services is important in reducing inequality and increasing agricultural productivity. This requires a multi-sectorial response and approach that includes complementary food, public health, and education systems. In addition, better nutrition can be achieved along both traditional and commercial food supply chains by responding to consumer needs and market demands in the food system. The mainstreaming of indigenous crops has also been identified as having a key role in ensuring food security in this time of increased climatic variation, as these species are adapted to local harsh climatic conditions.

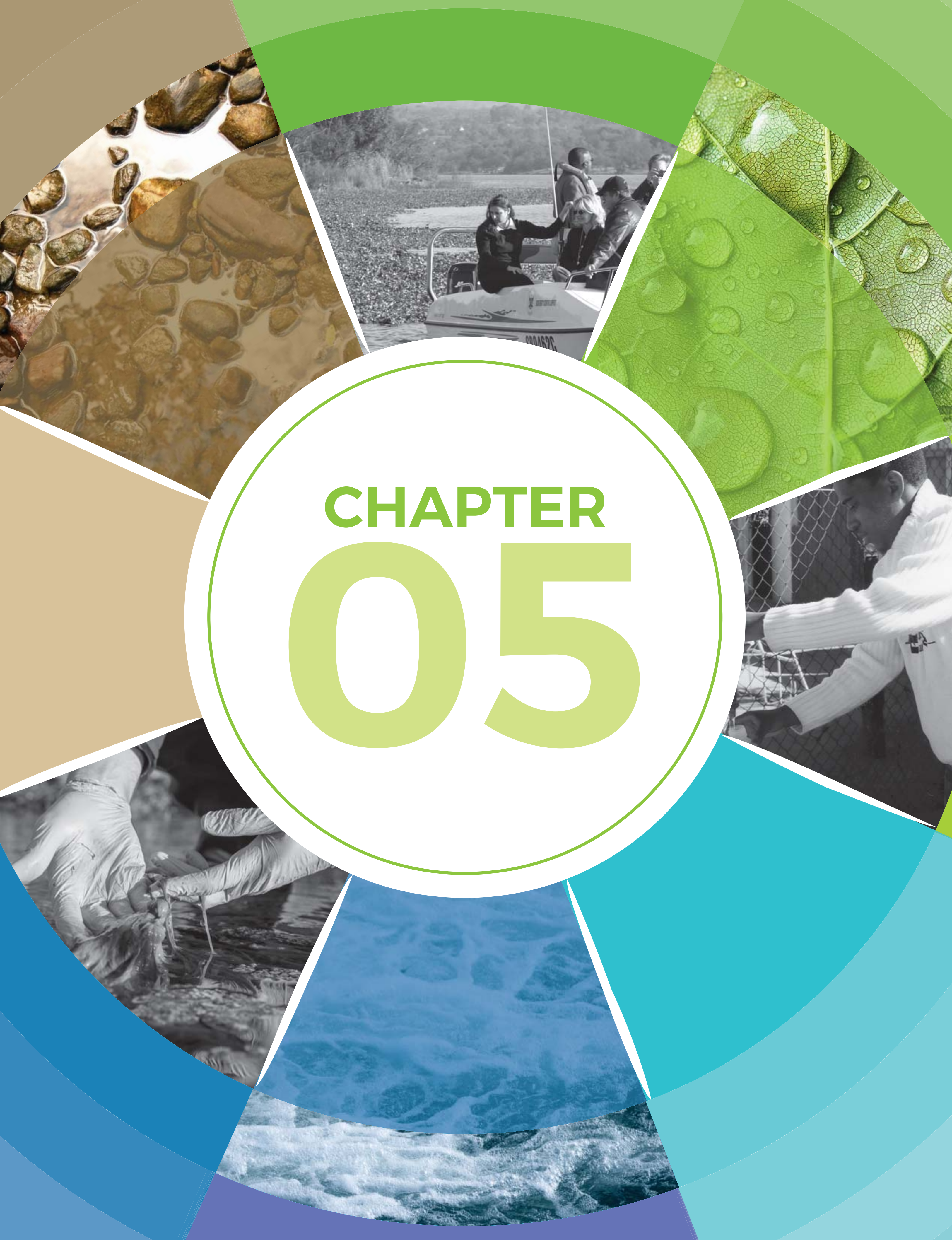
The application of transformative approaches has become important in dealing with the current challenges; the circular economy, the WEF nexus, scenarios planning, and sustainable agricultural systems are amongst the proposed strategies to be adopted going forward. This will require investment in the development and adoption of 'smart' solutions for water-use efficiency. The emphasis should be on developing appropriate institutional and organisational arrangements and policy interventions that will focus on the entire food system.

Concluding remarks: Embracing the fourth industrial revolution (4IR)

Remote sensing (including drones) has become an important component of irrigation management, particularly in irrigation scheduling (Nhamo et al., 2020b). Remote sensing products that can pinpoint areas of wet and dry zones in cultivated fields and estimate crop water requirements are freely available (Nhamo et al., 2020b). Such information is vital for irrigation scheduling. In addition, mobile apps and other social media platforms can provide information on weather, rainfall, and soil humidity to allow better farm management and productivity and information on markets (Amarnath et al., 2018).

The WRC's Water Utilisation in Agriculture portfolio (KSA 4) has funded projects that form part of the fourth industrial revolution (4IR), and include: the use of remote sensing products and services in the agriculture sector to enhance agricultural water management and ensure water-use efficiency through:

- modelling crop evapotranspiration to inform irrigation scheduling
- accurate mapping of irrigated areas to inform policy on irrigation expansion
- crop stress and health analysis in near real-time for informed intervention strategies
- estimating crop water productivity



CHAPTER 05

WATER QUALITY AND POLLUTION – PROTECTING THE HEALTH OF PEOPLE AND WATER RESOURCES

Nonhlanhla Kalebaila and Eunice Ubomba-Jaswa

INTRODUCTION

Water is one of the most essential natural resources for all life on Earth. The availability of adequate and suitable (in terms of quality) water plays an important role in supporting its many uses, such as domestic, agricultural, industrial, recreational, and environmental activities, and general economic development. Like other nations, South Africa has been transitioning through the different eras of industrialisation with many successes up to the present day. Since the discovery of large diamond deposits in Kimberley in 1867 followed by that of gold in the Witwatersrand in 1886, South Africa changed rapidly from an agricultural society to an industrial society.

The dawn of the twentieth century was characterised by an unprecedented rise in the rate of population growth and increased use of water resources for supporting both domestic uses and mass production of food and manufactured goods. In turn, this exerted significant pressures on the available water resources, leading to widespread water pollution and stress around the country. The awareness around the scarcity of water, coupled to the water quality situation at that time led to the promulgation of the Water Act (Act No. 54 of 1956). The Water Act of 1956 (Act No. 54 of 1956) made it obligatory that only purified effluents could be discharged to a watercourse. Permits were required to use water for agricultural purposes and to discharge effluents not complying with the quality standards. From that time till the late 1960s, the question of how to efficiently manage the nation's limited water resources in terms of both quantity and quality became a subject of intense interrogation by academics, economists, and policy makers alike. It is against this backdrop that in the early 1970s the Water Research Act (Act No. 34 of 1971) was promulgated, which paved way for the establishment of the Water Research Commission (WRC).

Soon after establishment, the WRC developed the first national Water Research Masterplan (Water Research Commission, 1973)*, placing water quality management issues at the centre of water and environmental resource management and sustainable development. Regarding water quality management, the focus of the WRC has been directed towards mitigating the impact of different pollution sources and land-based activities on water quality, as well as monitoring the quality of water based on established water quality criteria. Throughout its existence, the WRC has also addressed several issues concerning water quality and pollution, including spearheading research on water use and management of municipal, industrial, mining, and agricultural effluents, leading to the development and deployment of innovative treatment technologies, as well as adoption of policies and strategies for pollution management. Research funded by the WRC has also been instrumental in setting the stage for the promulgation of post-democracy national water policies and legislation, such as the National Water Act (Act No. 36 of 1998) and National Water Resources Strategy, which reflect the country's vision for sustainable and integrated water quality management. This research-to-policy concept has been deeply embedded within the strategic objectives and core values and principles of the WRC since its establishment (WRC)*.

The evolution of water quality and pollution research in South Africa

The mandate of the WRC was designed around interrogating the ideologies of the Golden Age of Capitalism, which were pro-industrialisation in the context of water resources management. In terms of water quality, the WRC was tasked with investigating the pollution of water resources by different activities, to support the development and implementation of sustainable national plans for water resources monitoring and the prevention of pollution. In terms of water quality, the following areas were identified as priority.

- **Municipal water supply and quality management,** including an assessment of purification processes, considering the quality of the raw water, monitoring systems, distribution systems, quality criteria, drinking water quality and health aspects, and municipal water supply management.

- **Irrigation water quality** and its effect on soil and crops, as well as pollution and mineralisation of irrigation water.

- **Water reclamation, focusing on** quantifying effluents discharged by different water-use sectors, effluent treatment process development and optimisation, developing health-based water quality criteria for human, animal, agricultural and industrial water reuse, development of guidelines for implementing water-reuse schemes.

- **Prevention of pollution, with specific attention to** domestic and sewage effluents, industrial effluents, mining effluents, agricultural effluents and runoff, storm water and surface pollution. Furthermore, this theme also included execution of water quality surveys of rivers, estuaries, dams, lakes and the sea, development of water quality criteria for freshwater environments (specifically those for human use) and effluents, establishing water quality monitoring parameters, measurement, and evaluation of specific pollutants, as well as supporting the development of related legal and administrative procedures.
- **Groundwater management,** focusing on quantitative and qualitative determination of groundwater supplies

- **Water desalination,** focusing on occurrence, utilisation, detection, and quantitative assessment of mineralised water along the Republic's coastline and in the interior; cost benefit studies of desalination in specific areas for seawater, brackish water, and mineralised effluents, as well as evaluation and development of desalination processes.

Since inception, the WRC has made significant research investments aimed at elucidating the contribution of water use activities, as well as natural processes on water resources quality.

Influences of natural factors on water resources quality

To date, a great deal of WRC research has established the influence of natural processes, such as depositions due to wind (Skoroszewski, 1999)*, weathering of rocks (Vegter, 2001)*, leaching from soil ((van Huyssteen, et al., 2007)*, runoff due to hydrological factors, and biological processes in the aquatic environment, on water quality (Palmer, et al., 2004)*. Research on the impact of these processes in effecting changes in the water pH and alkalinity, and thus resulting in high concentrations of sulphates (Pollution Research Group, 1990)*, phosphorus (Weddepohl & Meyer, 1992)*, fluoride (McCaffrey & Willis, 2001)* in water is also well established.

Eutrophication

Apart from research studies on water pollution because of the discharge of poor-quality industrial wastes, eutrophication due to the discharge of high nutrient loads (mainly of phosphorus and nitrogen) into water bodies has also been an area of intense research since its discovery in the 1970s (Walmsley, et al., 1978). The WRC has been extensively involved in eutrophication research since its inception (Water Research Commission, 1973)*. Figure 1 indicates the research focus split across the categories of eutrophication issues, over the period from 1984 to 2009 (Frost & Sullivan, 2010)*. Agricultural runoff, domestic sewage, industrial effluents (with a significant phosphate load coming from detergents, especially washing powders) and atmospheric inputs from fossil fuel burning and bush fires, have been identified as main sources for high nutrient loads in water systems, bringing concomitant problems of aesthetics, health, recreation and water treatment (Grobler & Silberbauer, 1984)*; (Simpson, 1991)*; (Pegram , et al., 1998)*. By the year 2010, the WRC had published approximately 84 research studies (Frost & Sullivan, 2010)*, addressing different issues related to assessing the extent of the eutrophication problem (Walmsley, 2000); (Downing & van Ginkel, 2004)*, and the development and testing of innovative water treatment technologies and strategies for managing the problem (Linde, et al., 2003)*.

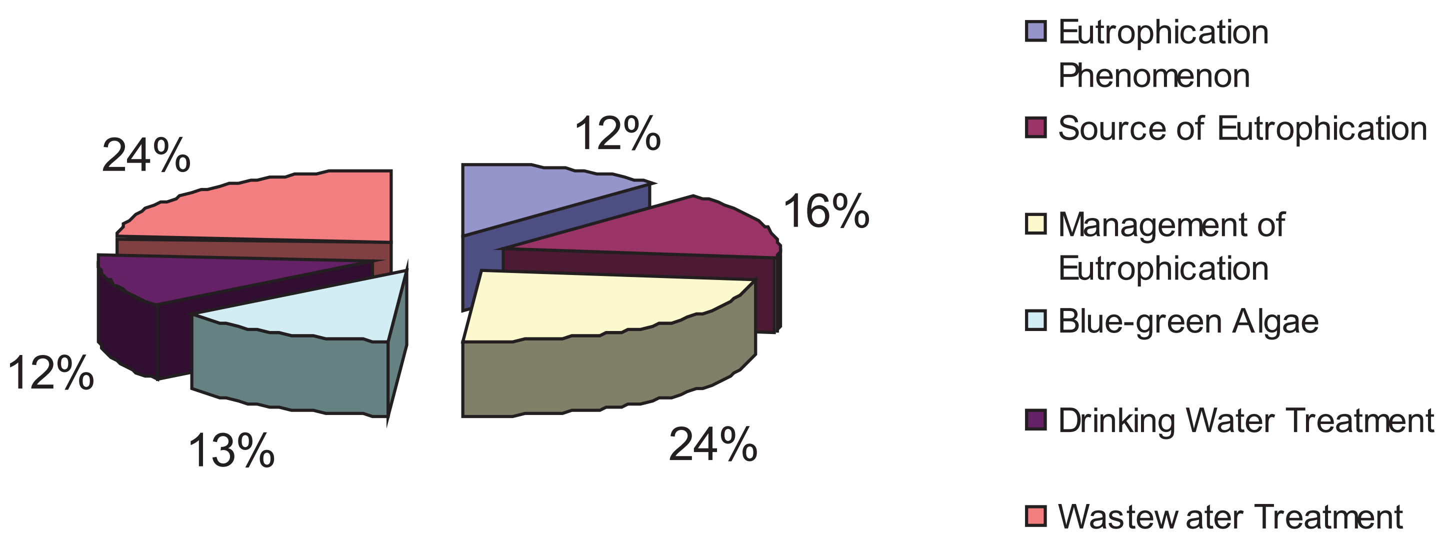


Figure 1. Categories of eutrophication-related research conducted by the WRC between 1984 and 2009 (Frost & Sullivan, 2010)*.

Figure 2 indicates the transition in eutrophication research funded by the WRC from basic research related to understanding the problem and its impacts to generation of knowledge for its management and treatment (Frost & Sullivan, 2010)*. The economic, environmental, social and health impacts of eutrophication related research conducted under the auspices of the WRC has been reported by (Frost & Sullivan, 2010)*. It is widely acknowledged that minimising the entry of high nutrient discharges into freshwater systems is the most effective strategy for preventing eutrophication. The WRC project on the consequences of introducing zero-phosphate detergents (Quayle, et al., 2010)* provided crucial information on the contribution of detergent phosphates to the phosphate loading at wastewater treatment facilities and explored the potential impact of introducing low- to zero-phosphate detergents into South Africa. Findings from this project served as a further important step towards active control of eutrophication in South Africa since the implementation of the 1 mg/L P standard promulgated in 1980 (Chutter, 1989)*; (Frost & Sullivan, 2010)*. One of the success stories related to knowledge generated from all the eutrophication-related research conducted was the voluntary decision to remove builder phosphorus from detergents by one of the major producers (Frost & Sullivan, 2010)*.

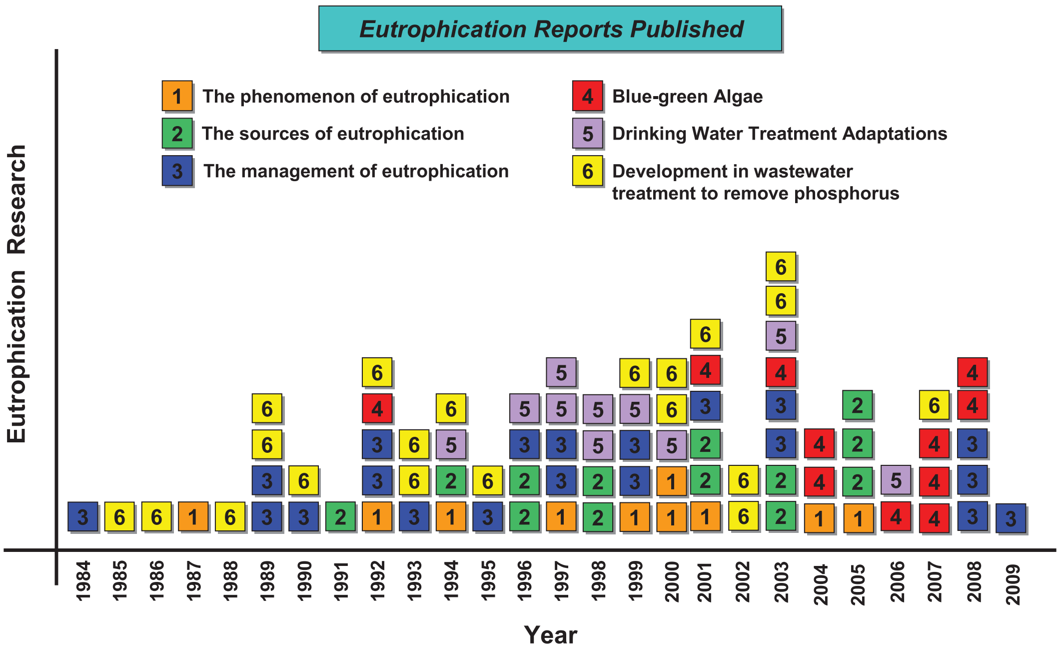


Figure 2. An overview eutrophication research report published by the WRC between 1984 and 2009 (Frost & Sullivan, 2010)*.

This aspect demonstrates the positive role of research in influencing decision-making in manufacturing practices, which assisted in reducing source (manufacturing) contribution of water pollution. However, there is still concern over eutrophication from diffuse pollution sources, such as increased fertilizer application (Dabrowski, 2015)*. The current eutrophication status of most water bodies in the country suggests that managing eutrophication requires a combination of source-directed controls and resource-directed measures (Griffin & Palmer, 2014)*.

Figure 3. Eutrophication remains a challenge in various water bodies, such as the Hartbeespoort Dam. (Credit: Heidi Snyman)

According to (van Ginkel, 2011) integrated management of eutrophication requires continued and sustained efforts towards monitoring; enforcement of water pollution control regulations aimed at reducing the release of phosphorus into water resources; the generation of adequate knowledge encompassing all efficient and viable eutrophication-management options for South African climatic conditions and social requirements; in-lake management options for sites that are already hypertrophic; strengthening the implementation of effective eutrophication-management methods at impacted sites and ensuring adequate funding and efficient expenditure to combat the problem of nutrient enrichment of freshwater resources in a sustainable manner. Advances in the monitoring of eutrophication have occurred, through the WRC funded project, the Earth Observation National Eutrophication Monitoring Programme (EONEMP). Phase 1 of the project saw a successful combination of earth observation technology and real time sampling to monitor eutrophication in dams in the country. This tool is not only being used in South Africa but also internationally (Matthews, 2016).

Monitoring the impact of industrial water use activities on water resources quality

Research work tracking the evolution of water quality because of water use and waste generation in manufacturing industries began as early as the 1980s, through a joint effort by the WRC and the Department of Water Affairs (now Water and Sanitation). Under this initiative, the water use, wastewater generation volumes and wastewater management practices in different industries have been assessed through National Industrial Water and Wastewater Surveys (NATSURVs) (SA Waterbulletin, 1984). The earliest surveys were conducted through physical visits by experts who performed tests and collected the necessary information on site.

By the early 1990s, the first set of NATSURV reports had been published by the WRC, covering the malt brewing, metal finishing, soft drink and carbonated waters, dairy, sorghum malt and beer, edible oil, red meat, laundry, poultry, tanning and leather finishing, textiles, pulp and paper, sugar, and wine industries (Steffen Robertson & Kirsten Inc, 1991)*. In 2012, a revision process for these NATSURV report series was initiated as means of determining shifts in the types of industries that are in operation and related wastewater management practices, and to provide updated intelligence on the contribution of industrial water use to water resource pollution. Over the years and to date, the generated NATSURV reports have played a significant role in promoting best practices for water use efficiency and wastewater management in these sectors. The impact of the knowledge generated through these surveys has been manifested by shifts in water quality management practices in industry, and the new wastewater treatment technologies and systems that have been developed and deployed in industry today (African Centre for a Green Economy, 2018)*.

Figure 4. An assortment of the National Industrial Water and Wastewater Surveys (NATSURVs) completed since the start of the revision process in 2012.

Mining and water quality

Industrial scale mining in South Africa began in the 1850s and, as such, mine dumps in mining towns and their surroundings have been a feature of the South African landscape for centuries. Today, acid mine drainage (AMD) is one of the major environmental problems associated with mining activities in South Africa. The WRC has been involved extensively in minewater management research since 1989. A WRC report by (Frost & Sullivan, 2011)* provides a comprehensive account of the contribution of WRC research on managing AMD in South Africa (Figure 5).

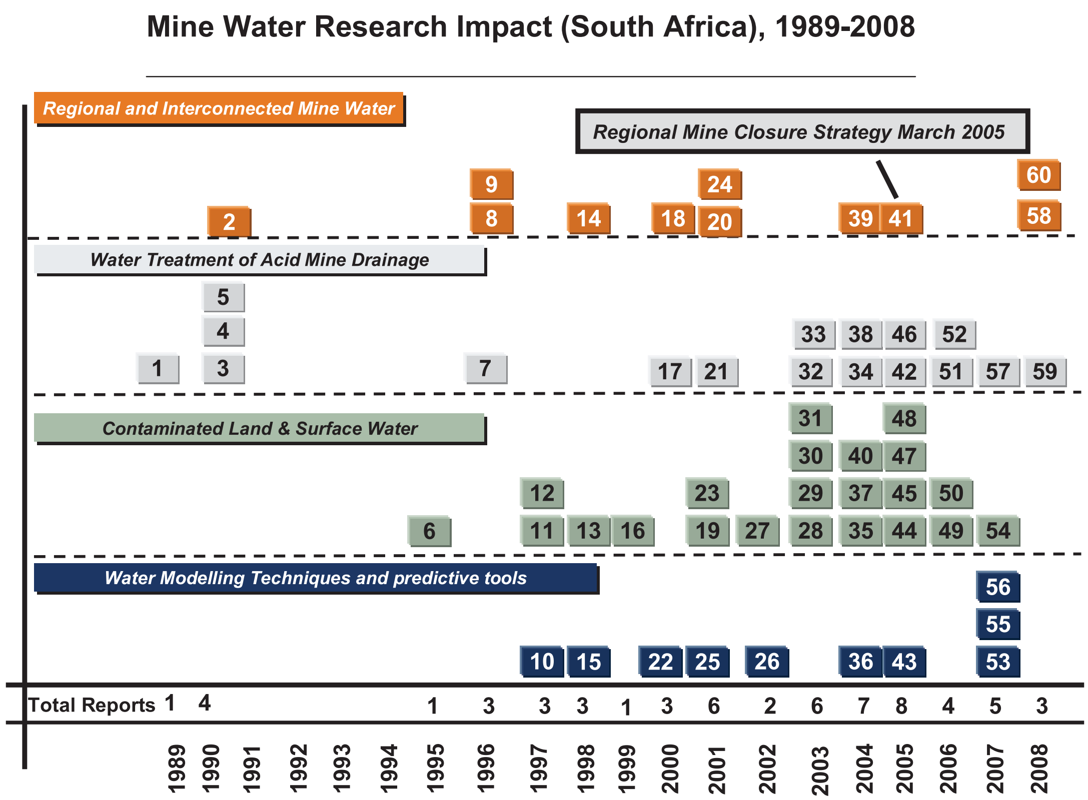


Figure 5: Schematic showing the contribution of WRC-funded research in managing water quality impacts from mining activities. The different colours denote the key research themes, and the numbers 1-60, denote the sequence of research reports published under each theme (Frost & Sullivan, 2011)*.

According to this report, the WRC, has over the years made significant contributions on the following themes:

- Expounding the impact and extent of mining on the surface water environment.
- Facilitating the development and adoption of innovative treatment options for mine effluents and the rehabilitation of mine soils.
- Development of modelling techniques and predictive tools for assessing the impact of mine effluents on water resources; and
- Providing guidance on sustainable mine closure and the reuse of mine-affected water for non-potables purposes, such as irrigation (Frost & Sullivan, 2011)*.

Earlier WRC-funded research focused on the water requirements and impacts of gold and uranium mines on water resources quality. The period from 1995 to 2005 was dominated by research on the impact of mining on the surface water quality and development of water modelling systems for the mining industry as well as sector-wide options for mine water treatment and management. Recently, much of the work funded by the WRC has shifted focus into providing guidance on sustainable mine closure (Pulles, 2015)* and reuse of mine-affected water for non-potable uses, such as irrigation (Annandale, et al., 2018). WRC-funded research on sustainable mine closure has led to the development of the first *South African Mine Water Atlas* (Water Research Commission, 2018)*. This atlas is a comprehensive reference of the vulnerability of water resources to mining activity in South Africa and shows the critical interplay between mining and water resources and is the most extensive set of documents of its kind.

Figure 6. South Africa's first Mine Water Atlas was published by the WRC in 2018.

Impact of domestic wastewater discharges, stormwater, and agricultural runoff on water quality

This section highlights WRC-funded work on establishing the contribution of poorly treated municipal wastewater effluents, stormwater, and runoff from agriculture and unserved settlements in raising the nutrient and salt levels and the transfer of pathogens and chemicals of concern into water resources. With regards to pathogens, considerable work has been commissioned by the WRC to determine the presence of waterborne pathogens in water and possible linkages to related disease incidence (Grabouw, et al., 1996)* (Venter, 2003)*; (Said, et al., 2005)*; (Lin, et al., 2012)*; (Ntema, et al., 2014)*; (Potgieter, et al., 2018)*; (Mhuka, et al., 2020)*. Internationally, awareness of the detrimental impacts of exposure of living organisms, including humans, to chemicals in water can be traced as far back as the 1960s, where (Carson, 1962) detailed the ecological impacts related to widespread usage of pesticides, such as DDT (dichloro-diphenyl-trichloroethane) to eliminate mosquitoes and other pests. By the beginning of the 21st century, there was global consensus that exposure to chemical compounds through ingestion, inhalation and dermal contact with contaminated water can have adverse effects on living organism, including interfering with the endocrine system.

According to the Hormone Health Network (Hormone Health Network, 2021), endocrine disrupting compounds (EDCs) are defined as chemicals that interfere with the structure or function of hormone-receptor complexes. They can cause endocrine disruptive effects at exposure levels up to a million times lower than carcinogen exposure levels of concern. As such, the WRC, under a directive from the Global Water Research Coalition (GWRC), spearheaded the first report on the occurrence of endocrine disrupting compounds (EDCs) in water in GWRC member countries (WRC, et al., 2003)*. After this, the WRC research programme on EDC was launched in 2005 (Burger, 2005)*. It was around this time that the term, "emerging contaminants of concern" was also established (Field, et al., 2006), to collectively refer to all chemical compounds that have a potential to exert adverse effects on environmental and human health.

Given that the intensity of agriculture in South Africa is so high, the country is amongst the highest user of agrochemicals in sub-Saharan Africa (Dabrowski, 2015)*, consequently there has been comprehensive research on the contamination of water resources by the over 8 000 pesticide formulations registered for use. Several WRC studies have highlighted the occurrence of pesticides such as DDT (Bornman, et al., 2009)*, herbicides, or fertilizer compounds in non-target environments in South Africa, particularly in ground and surface water (Dabrowski, 2015)*. By the late 2000s, the presence of wide variety of emerging contaminants of concern, including those of biological origin, were reported to occur water sources around the world, prompting the introduction of the term, "emerging substances of concern" (Florida Department of Environmental Protection, 2008). Emerging substances of concern (ESOC) include global organic contaminants, endocrine disrupting chemicals (EDCs), nanoparticles, and biological metabolites.

In summary, work funded by the WRC to date on the water and effluent problems of municipalities, and the mining and power generation and other industries, has already yielded valuable information, which has served as a precursor to the development of several mechanisms for water quality monitoring, environmental risk assessment and pollution management.

Water quality monitoring, risk assessment and health

Countrywide water quality monitoring is a common practice all over the world. In 1991, the WRC's Co-ordinating Committee for Health-related Water Quality held a strategy session aimed at developing a master research plan for water quality and health (Water Research Commission, 1992)*. The primary goal of the master plan was to guide the implementation of projects related to the impact (actual or potential) of water quality and human health for specific user sectors (domestic, recreational, industrial, irrigation and aquaculture), with a view to establishing research needs in this field. This plan also prioritised research on the development of water quality monitoring programmes and guidelines for water quality, analytical methodology, information, and technology transfer, as well as assessing the efficiency of water treatment technology with reference to human health. The WRC Water Quality and Health programme has slightly evolved over the years, with the current focus being on issues related to water quality, health, and sustainable development (Water Research Commission, 2014)*. It is the view of the WRC that water quality is a crucial consideration for efficient water resources management and sustainable development. Water quality monitoring and human health risk assessment research supported by the WRC has over the years advanced from the use of quantitative risk frameworks (e.g. quantitative microbial risk assessment, QMRA, for microbial pollution (Boyd, et al., 2010)*, to the use of effect-based methods for water safety planning (Aneck-Hahn, et al., 2017) (KWR, 2021).

Development of water quality monitoring programmes

An initial water quality monitoring strategy was formulated in 1992 (Harris, et al., 1992)* and submitted to the Department of Water Affairs and Forestry as a tool for assessing water quality on a national scale. The strategy resulted from a research project carried out in terms of a shared agreement between the WRC, the CSIR and the Department of Water Affairs and Forestry. To date, WRC research has significantly contributed to the implementation of the different national water monitoring programmes. Examples include, the River Health Monitoring Programme (Hill, et al., 2001)*; a National Microbial Monitoring Programme (NMMP) developed by the then Department of Water Affairs in 2002, at which stage a decision was made to expand the programme to include microbial monitoring of ground water (Murray , et al., 2004)*; a dedicated National Microbial Monitoring Programme for groundwater (Murray, et al., 2007)*; and a recent revision of the National Wetland Monitoring Programme (Sustento Development Services, 2016)*, to name a few. Water quality of rivers, wetlands and estuaries is discussed in each of the relevant chapters in this book. More general reports on environmental water quality include (Palmer, et al., 2004)* and (Griffin & Palmer, 2014)*.

Monitoring known and emerging substances of concern in water environments

Since establishment of the WRC programme on Water Quality and Health, the WRC has been at the forefront of research on monitoring of known and emerging substances of concern (ESOC) in water environments. With regards to chemicals, the presence of chemicals of concern such as, persistent organic pollutants (POPs) (Roos, et al., 2011)*, pharmaceuticals and personal care product and industrial compounds (Archer, et al., 2020)*; (Okonkwo, et al., 2015)*; (Mhuka, et al., 2020)*, microplastics (Bouwman, et al., 2018)*, EDCs (Meyer, et al., 2014)*, has been reported. Similarly, several WRC-funded research has contributed significantly to our understanding of pathogenic microbial contamination in South Africa's water resources, including our aquatic ecosystems. The diversity of aquatic microbial populations has always been difficult to assess but today, molecular techniques allow rapid and detailed analyses of these populations. Vosloo, et al., (2018)* describe the diversity and dynamics of microbial populations associated with several drinking-water distribution systems, while Okoh, et al., (2015)* examined faecal indicator bacteria and ***Vibrio*** pathogens in wastewater effluents in the Eastern Cape.

WRC-funded research has also led to the identification and measurement of several different pathogens. Grabow, et al., (2003), for instance, developed a technique for specifically detecting the highly pathogenic strain of ***E. coli,*** 0157:H7 and developed a technique for identifying heterotrophic plate-count bacteria, which include opportunistic pathogens otherwise difficult to identify. Novel techniques include the identification of faecal coliforms using an electronic biosensor system (Pletschke, et al., 2008)*. Other new techniques allow the identification of non-specific pathogenicity. Jagals, et al., (2006)*, for instance, developed a method for assessing inflammatory potential of human receptor organs, which can be used as a general indicator of pathogenic conditions in water, even where specific pathogens have not been identified. Similarly, Genthe & Franck (2003)* developed and investigated the usefulness of simple test strips for identifying potential microbial contamination in waters where access to a laboratory is not available, while Tandlich, et al., (2012)* investigated the use of additional methods for identifying faecal contamination in regions where the NMMP does not reach. Finally, certain WRC-funded projects have addressed problems associated with newly emerging microbial pathogens. Venter (2003)* surveyed certain pathogens (e.g., viruses causing haemorrhagic fevers; bacteria such as Campylobacter; and protozoan parasites such as Cryptosporidium and Giardia) in source and treated waters, while Bailey & Jarmey-Swan (2003)* developed immunoassays for Cryptosporidium and Giardia and van der Walt & Grundlingh (2014)* investigated the most effective ways of inactivating these protozoans.

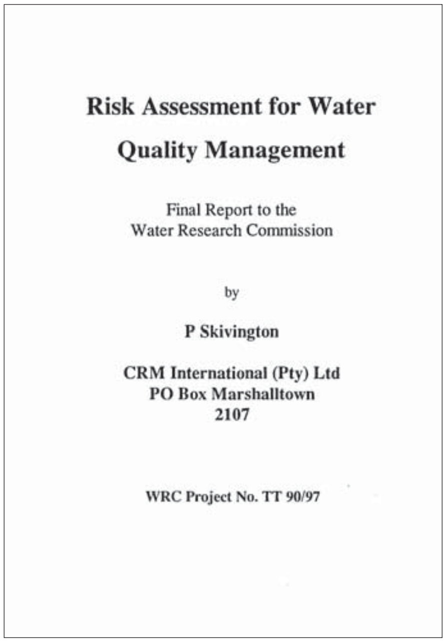
Over the last few years, the occurrence and persistence of pharmaceuticals and other chemical stressors in the environment, in water resources, has reached alarming levels, and has been identified as an emerging policy issue of concern due to their contribution in the development of antimicrobial resistance (AMR) (SAICM, 2019). AMR occurs when bacteria, viruses, fungi, and parasites develop or acquire resistance genes, such that they no longer respond to the drugs meant to treat the infections they cause, making infections harder to treat and increasing the risk of disease spread, severe illness and death (World Health Organisation, 2020). Therefore, a number of WRC research projects have addressed, both the occurrence of drugs (pharmaceutical products) such as antiretrovirals (ARVs), antibiotics and resistance genes in different water sources (Cowan, et al., 2011)*; (Okoh & Sibanda, 2015)*; (Bezuidenhout, et al., 2019)*; (Archer, et al., 2020)*. The enigma of pharmaceuticals occurrence and the development of antimicrobial resistance in aquatic environments, as well the emergence of new substances of concern is expected to dominate water quality research going into the future.

Environmental and human health risk assessment

Exposure to each of the substances highlighted above, through ingestion, inhalation, or dermal absorption, has been shown to pose significant risks to ecosystems and human health. Health risk assessment is a process to determine the nature and probability of adverse health effects in living organisms who may be exposed to contaminated water. According to the World Health Organisation (World Health Organisation, 2018), there are two main approaches to health risk assessment, namely:

- The parameter approach, in which the estimation of the risk related to the use of water is based upon the presence of different parameters (i.e., chemicals and microorganisms). This approach is based on either the water quality standards or quantitative risk assessment — where toxicological data, and data on infectious doses and acceptable risk (chemical and biological) are taken as a reference.
- Effect based approach, a method of exposing test organisms, cells or tissues to the contaminated water and studying the health effects of the water to the test organisms or on the population.

One of the earliest documents on risk assessment published by the WRC, was a guideline titled; ***Risk Assessment for Water Quality Management*** (Skivington, 1997)*. The approach followed for risk assessment in this document includes the use of mathematical models (quantitative risk assessment) and risks matrices to estimate the risk associated to exposure to contaminated water. This publication served as a reference document for the development of risk-based water quality guidelines for different uses in South Africa (Meyer, et al., 1997)*. Recently, these guidelines have been revised to incorporate the concepts of quantitative and site specific risk assessment for the development of risk-based and site specific water quality guidelines for irrigation (du Plessis, et al., 2017)*, domestic use (Moodley, et al., 2020)* and recreational water use (Genthe, et al., 2020)*.



Risk Assessment for Water Quality Management

Final Report to the
Water Research Commission

by

P Skivington

CRM International (Pty) Ltd
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WRC Project No. TT 90/97

Figure 7. The 1997 report by Skivington (1997) was one of the first publications printed by the WRC on risk assessment.

The use of biological approaches to measure and evaluate the consequences of anthropogenic actions on water quality (bioassessment), particularly in rivers, is commonly practised in South Africa. The well-known South African Scoring System, SASS, which uses invertebrates as indicator organisms, was developed by Dr Mark Chutter in a WRC-funded project (Chutter, 1998)*. SASS has proved invaluable in assessing aspects of the biotic integrity of rivers. Unfortunately, it is not suitable for wetlands (e.g., Bird, 2009)* and yet no other indicator system has proved useful in this regard.

Various ecotoxicological studies were funded by the WRC, particularly in the 1990s. An outdoor artificial stream system was erected at Rhodes University in the early 1990s (Palmer et al 1996)*, on the understanding that regular laboratory-based ecotoxicological analyses are constrained by the unnatural conditions encountered in vitro. At the same time, the Rhodes team identified several invertebrates as suitable test organisms (Muller & Palmer 2002*, Scherman, et al., 2003*, Muller, et al., 2011*). Several reports (e.g., Palmer, et al., 2004* and Griffin, et al., 2011*) emanated from experiments using these taxa in the artificial stream. Other ecotoxicological work included an analysis of the effects of Al and Cu toxicity in the peat-stained black waters of the fynbos biome (Dallas, et al., 1998)*.

Regarding chemical risks, it is being increasingly recognised, however, that targeted chemical monitoring and traditional (quantitative) risk assessment methods cannot account for all the risks associated to exposure to emerging (unknown and unregulated) chemicals of concern and their transformation products, as well as chemical mixtures. Understanding risks associated with exposure to emerging contaminants in water requires a paradigm shift from the current approaches that reflect only a fraction of the overall chemical risk to those that allow for a more holistic assessment. Globally, there is a growing interest in the application of effect-based methods (EBMs) for toxicity-pathway-based water quality monitoring and risk assessment.

EBMs involves the use of specific toxicological endpoints, such as carcinogenesis, adverse effects on reproduction and development, effects on xenobiotic metabolism (i.e., the transformation of synthetic chemicals once in our bodies), modulation of hormone systems, DNA reactivity, and adaptive stress responses, for water quality assessment and risk management. To date, a battery of ecotoxicological assays, including in vitro cell based assays and in vivo whole-organism bioassays, have been developed and tested for water quality monitoring under WRC projects. Similarly, there have been attempts to develop a toolbox for EDC health-risk assessment ((Aneck-Hahn, et al., 2017)*. Currently, efforts are underway to revise this toolbox by developing an all-inclusive toolbox, comprising of a suite of bioassays each targeting different biological pathways and providing guidance on their selection, interpretation, and application for water quality assessment.

With regards to microbial risk management, several projects have developed guidelines for the identification and management of specific infectious diseases, for example legionellosis (Coubrough, 2003)* pathogenic strains of ***E. coli*** such as 0157:H7 (Grabow, et al., 2003)*; and viruses (Grabow, et al., 2004). Still others have assessed the extent of microbial contamination in specific areas of the country: faecal coliforms in the Amathole district (Okoh, et al., 2012)*; and microbial pathogens in the Umgeni catchment (Lin, et al., 2012)*, the Mhlatuze River (Lin, 2004)* and the North-West Province (Bezuidenhout, et al., 2013)*.

Use of wastewater-based epidemiology for monitoring public health

Current research conducted under the Water Quality and Health portfolio of the WRC explores the potential of wastewater-based surveillance for monitoring the health of communities. According to (Kasprzyk-Hordern, 2019), the concept of wastewater-based epidemiology (WBE) is an integrated technique related to the extraction, analysis, data processing, and interpretation of targets (so-called biomarkers) excreted from faeces/urine in wastewater, which provides comprehensive community health information. This means that, a great deal of information can be extracted from the analysis of the untreated wastewater collected from identified communities that are served by the surrounding wastewater treatment plant. The analysis of the untreated wastewater for specific biomarker compounds (such as metabolites or endogenous chemicals resulting from exposure to and/or disease) can provide an indication of the lifestyle habits and general health status of the community population in real time. To date, the concept of wastewater based epidemiology (WBE) has been exploited for assessing illicit drug abuse in communities (Archer, et al., 2020)* and also for monitoring COVID-19 infections in communities (Pocock, et al., 2020)*.

State-of-the-art in water/wastewater treatment and reuse

Water and wastewater treatment is part of the core principles of water quality management. Since inception, the WRC has made remarkable strides in the development and adoption of biological and chemical water treatment methods and processes. One of the well-studied processes in South Africa is the Biological Nutrient Removal (BNR) process pioneered by Dr James Barnard, a South African-born technologist (WaterWorld, 2011). By 1972, Dr Barnard had achieved a four-stage process that removed nitrogen from water at a rate of more than 92%, without the addition of chemicals and two years later, had developed the foundation for Enhanced Biological Phosphorus Removal (EBPR) (WaterWorld, 2011). Soon after the establishment of the Water Research Commission, research on biological nutrient removal was commissioned (Water Research Commission, 1973)*, resulting in the development of an operating manual for BNR in wastewater treatment works (Lilley, et al., 1997)*. As of today, this technology has been widely adopted in numerous wastewater treatment works around the globe (WaterWorld, 2011). Thus, the BNR technology is widely regarded as one of the most important wastewater treatment technology innovations to been developed in South Africa. The pioneers believe that the technology can be further enhanced by commissioning further research aimed at improving membrane characteristics of BNR plants (WaterWorld, 2011).

The development and application of membrane technology for water and wastewater treatment in South Africa started as early as 1986 under a WRC-funded project awarded to the Institute of Polymer Science at Stellenbosch University (Jacobs, et al., 1999)*. By the early 1990s, membrane science and technology development in South Africa for drinking water and wastewater treatment had advanced considerably and was regarded as one of the exciting possibilities for water quality management. Further research on membrane technology has also resulted in the development of reverse osmosis and its implementation in water reclamation and desalination.

Current research conducted at the WRC focuses on the development and testing of innovative and emerging treatment and resource recovery ("circular economy" concept) technologies for improved environmental protection which translates into improved water quality (Zvimba & Musvoto, 2018)*. In the early 2000s, the WRC began to fund research into the use of nanomaterials in water purification, and concomitantly into contamination of the natural environment by a variety of nanoparticles. The first published report, by Schutte & Focke, (2007)* was titled ***Evaluation of nanotechnology for application in water and wastewater treatment and related aspects in South Africa***. Soon afterwards, Petrik & Ndungu (2012)* produced a review of nanotechnology in water treatment. Research on the interaction of water and nanotechnology was formalised following a report by Wepener et al (2013)* entitled *Framework document for a WRC research programme on engineered nanomaterials*.

Since that time several reports have investigated the use of nanomaterials in water purification. Chaúque et al (2016)* and Mahlalela et al (2018)* both examined the fate and behaviour of engineered nanoparticles in simulated wastewater treatment plants, while Musee et al (2014)* applied modelling techniques to similar investigations.

Many of the more recent studies have investigated a variety of nano-based materials for water treatment, some of which are for large-scale use and some for use at community level. For instance, both Momba et al (2010)* and Petrik et al (2012)* examined the use of nanotechnology-based clay filter pots, which are commonly employed in water filtration in small rural communities. Larger-scale investigations into nanofibre-based strategies for detection and removal of water contaminants have been carried out by Pletschke et al (2013)*.

While biosensors using nano technology are becoming common, yet the only WRC-funded project in this field is that of Iwuoha & Olowu (2015)*, who developed a nanobiosensor for measuring 17β-estradiol in municipal wastewater. As a result of the significantly increased used of nanomaterials over the last decade, WRC has also funded a 5-year study due to be completed in the later part of 2021 which assess the risk of nano- and macro-scale emerging contaminants in freshwater systems using experimental and modelling techniques.

In summary, the use of nanotechnology in the water field is becoming common, and we can expect to see further research in this field being funded by the WRC.

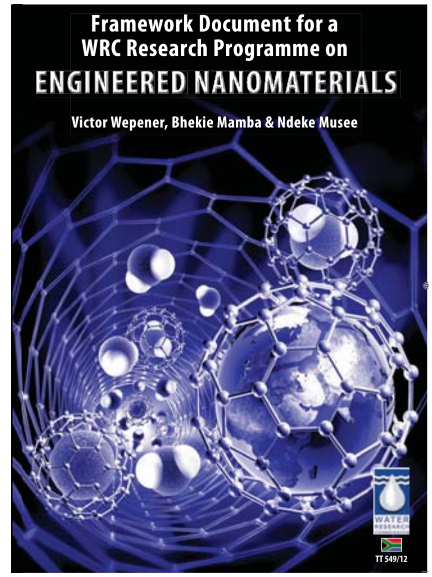


Figure 8. The WRC has published several studies related to nanotechnology including Wepener et al's Framework document for a WRC research programme on engineered nanomaterials, published in 2013.

Integrated water quality management: A reflection of research to policy transition

The steady degradation of water resources and pressing public health concerns related to water pollution triggered the initiation of several research studies, notably by the Council of Scientific and Industrial Research (Water Research Commission, 1973)*. Such studies enabled the promulgation of 'General Standards', 'General Authorisations', 'Special Standards' and 'Special Authorisations' for wastewater effluent quality over the period from 1962 to 1984 (Tempelhoff & Stopforth, 2014)*. Initial studies commissioned by the WRC in the early 1970s were a continuation of most of the studies initiated at the CSIR, addressing different water quality issues highlighted under an earlier section on the Evolution of Water Quality and Pollution Research in South Africa. This section provides evidence on how WRC-funded research has increasingly provided water quality managers with the legal tools required to manage water pollution, both from point and non-point (diffuse sources) over the years.

Collaborative research work by the WRC and the Department of Water Affairs and Forestry (DWAF) on non-point source assessment in South Africa was instrumental in the sanctioning non-point water pollution assessment as part of water resources management as stated in the National Water Act No. 36 of 1998 (Pegram, et al., 1998)*. The study by (Pegram, et al., 1998)* provided succinct policy recommendations for management of nonpoint sources in South Africa. The project further established the links between different non-point source assessment techniques and water quality management needs. The promulgation of the National Water Act enabled water quality managers to legally target non-point source pollution under specific source-directed regulations (Pegram, et al., 1998)*.

By the dawn of the 21st century, the WRC had generated sufficient water information, to support the development of the first National Water Resources Strategy in 2004 ((DWS, 2004), which provided a vision on how water resources in South Africa will be protected, used, developed, conserved, managed and controlled in accordance with existing policies and laws. It is under this strategy, the NWRS, that Resource Directed Measures (RDM) and Source Directed Controls (SDC) for water quality management were adopted. RDMs undertake to protect water resources by setting goals and objectives for the desired condition of water in aquatic ecosystems, while SDCs specify criteria for controlling water-use activities and their impacts on aquatic ecosystems. A 2004 WRC report by (Palmer, et al., 2004)* highlights some of the key WRC contributions to supporting the implementation of RDMs and SDCs, and highlights the following issues as research gaps that still needed to be addressed:

- Integration of the RDM components (Classification, Ecological Reserve, and RQOs) in order that their premises and the implications for practice are aligned.
- Integration of water quality and quantity processes to produce user-friendly quantity/quality models.
- Assessment and revision of RDM participatory processes.
- Integration to ensure coherent links between RDM and SDC measures at levels including policy, legislation, governance, and practice.
- Inclusion of a complex social-ecological systems view in research projects

The NWRS enabled the adoption of several global environmental governance and resource management concepts, most notably, integrated water resources management (IWRM), into national water policies and strategies (Palmer, et al., 2004)*. The concept of integrated water resources management (IWRM) is a well-documented framework, and it promotes the coordinated development and management of water, land and related resources, in order to maximize the resultant economic benefits and social welfare in an equitable manner without compromising the sustainability of vital ecosystems (Network of Asian River Basin Organizations & UNESCO World Water Assessment Programme, 2009). A WRC authored review paper by (Karar, 2008) provides a narration of South Africa's journey in the adoption of this concept. To partially address the lack of an integrated approach in water quality management, as highlighted by (Palmer, et al., 2004)*, the WRC initiated a project on Integrated Water Quality Management (IWQM) (Boyd, et al., 2010)*, The main aim of this project was to develop a conceptual model for aligning the management of the quality of water resources with that of drinking water quality in order to support the effective management of water use in the interest of all water users, an approach that guarantees the management of water in a catchment-to-consumer approach (Boyd, et al., 2010)* (Figure 9).

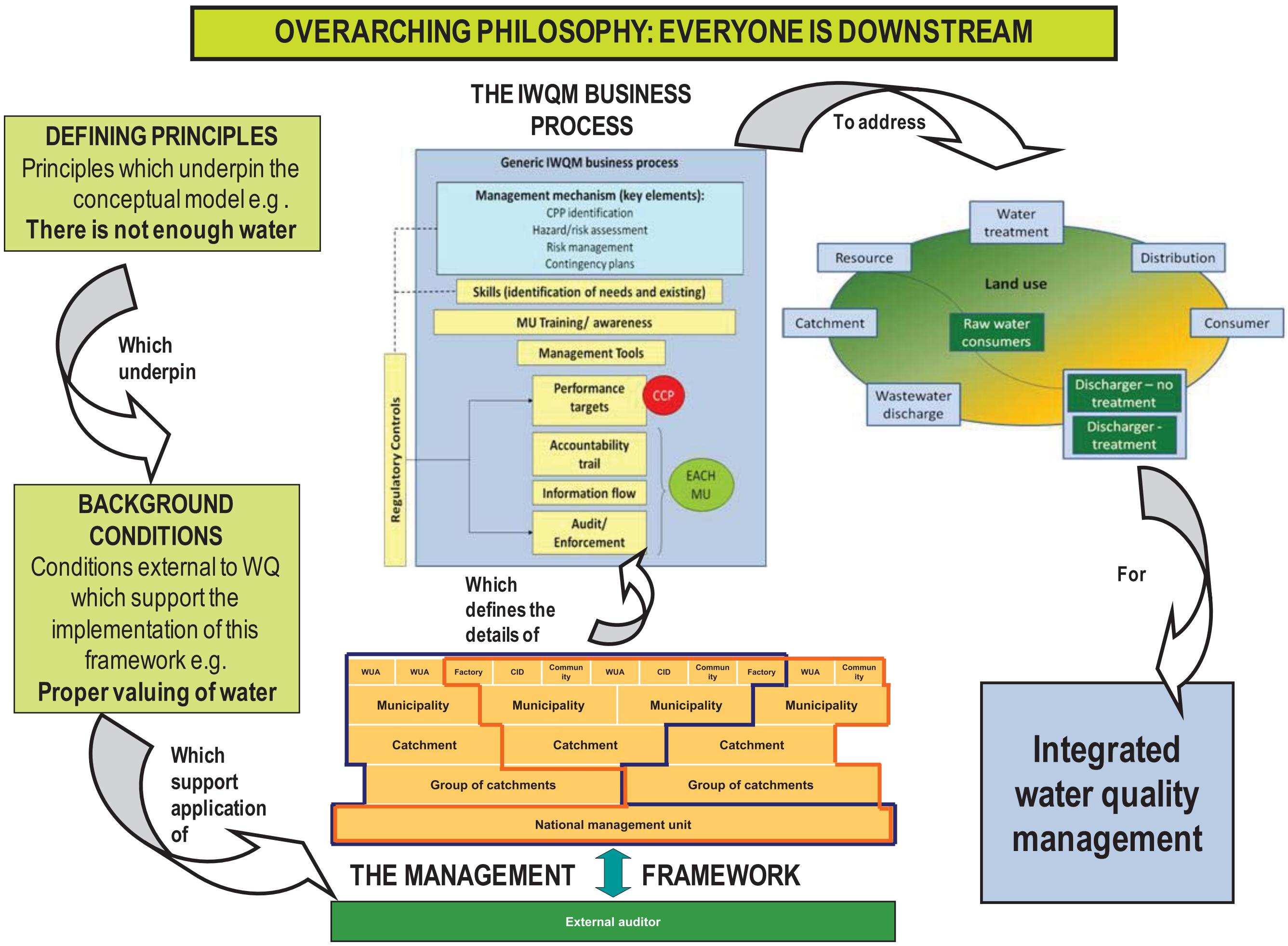


Figure 9. The integrated water quality management conceptual model (Boyd, et al., 2010).*

The IWQM model comprises of three main components, namely

- Defining principles which are defined as being generalisations that are accepted as true and that can be used as a basis for reasoning or conduct, such as water must be properly valued; institutions responsible for managing water must be accountable for water quality; water quantity and water quality are inextricably linked; the Polluter Pays Principle must be applied to the true cost of water pollution; short-term economic gain at the cost of increasingly deteriorating water quality is not acceptable; and everyone should have access to water quality information that may not necessarily be in the form of technical data. Background conditions which are defined as those conditions external to water quality which support the implementation of this framework and therefore indirectly impact on water quality, such as management systems and tools; and
- Management units which are defined as a geographical area that could be managed as a unit owing to common water use characteristics at the 'lower' levels and to institutional responsibilities with regard to the management of water quality at the 'higher' levels.

The main goal of integrated water quality management (IWQM) is to achieve specific objectives at a particular management unit, such as national management unit, and other established management units such as: municipalities;

catchment management agencies; water user associations, one or a group of industries; community, or a combination of these users. This notion implies that all water users are aware of their own responsibility for the protection of South Africa's water resources and are accountable for the impacts that they have on the resource. By implementing IWQM, each management unit will be empowered to address both current and future water quality challenges, such as climate change. As such the WRC study on integrated water quality management underscored the crucial role of IWQM in enabling strategic adaptive water resources management.

The concept of strategic adaptive management (SAM) as a framework for implementing integrated water resources management in South Africa has been explored by (Rogers & Luton, 2011)*; and by (Palmer, et al., 2018)* as part of the groundwork for the water resources management under different governance structures, such as, catchment management forums (CMFs), catchment management agencies (CMAs) and municipalities. In the recent WRC report by (Palmer, et al., 2018)*, SAM is defined, as using adaptive, systemic, processes and an understanding of complex social-ecological systems to coordinate conservation, manage and develop water, land and related resources across sectors within a given river basin, in order to maximise the economic and social benefits derived from water resources in an equitable manner while preserving and, where necessary, restoring freshwater ecosystems. Following the completion of the IWQM (Boyd, et al., 2010)* and SAM (Rogers & Luton, 2011)* research projects, the WRC in partnership with the Department of Water and Sanitation hosted a dialogue entitled "Preparing for an Integrated Water Quality Management Strategy for the SA Water Sector", in February 2015. Consequently, the current IWQM policies and strategies for South Africa incorporates an integrated, inclusive, and adaptive approach to water quality management (Department of Water and Sanitation, 2017).

Insights from WRC funded projects on the use of an Integrated Water Quality Management Model (IWQM) (Boyd, et al., 2010)* and findings from the WRC study on development of economic policy instruments for sustainable management of water resources (Maila, et al., 2018)* have also been instrumental in setting the stage for the establishment of pollution source directed water quality management strategy. The National Water Act mandates the Minister of Water, in consultation with the Minister of Finance, from time to time by notice in the Gazette, to establish a pricing strategy for charges for any water use within the framework of existing relevant government policy. The aforementioned WRC reports served as one of the catalysts in the development of the current National Water Pricing Strategy (DWS, 2015).

Another example of the contribution of WRC research on IWQM and SAM, relates to their integration in managing water quality in the context of climate change. A WRC-funded study by (Hughes, et al., 2014)* provides a detailed account on the linkages between climate change and water resources quality and provides guidance on water quality management in the context of future climate and development changes. This study further provides a recent detailed assessment of the effects of projected climate change on eutrophication and related aspects of water quality, as well as secondary impacts on aquatic ecosystems. Figure 10 shows the predicted water quality changes, in terms of nutrient release and algal prevalence because of climate change in selected areas in South Africa. From this study, it is evident that implementation of an adaptive water quality management approach along with continual monitoring is required as a strategy to cope with uncertainty associated with climate change and development.

Case Study		Berg River Dam		Voëlvlei Dam		Vaal River	
Model Used		CE-QUAL				QUAL2K	
Climate change projection dates		2046-2065	2081-2100	2046-2065	2081-2100	2046-2065	2081-2100
Parameter modelled	Phytoplankton					↑	↑↑
	Diatoms	↓#	↓#	↑#	↑#		
	Green algae	-		↑#	↑#		
	Blue-green algae	-		No strong trend #			
	Total algae	No trend #					
	Zooplankton	↓	↓	↑#	↑↑#		
	Water temperature	↑	↑			↑	↑↑
	Flow (river)/Level (dam)	↓	↓↓	↓	↓	↓	↓
	Dissolved oxygen	↓	↓	↓	↓	↓	↓↓
	Orthophosphate	Unchanged		↑	↑		
	Ammonium	↓	↓	↑#	↑↑#		
	Nitrate/nitrite	No trend		No trend #			
	Dissolved silicon	↓	↓	↑#	↑↑#		

↑	Increase (- approximately double magnitude of the increase into the distant future)
↓	Decrease (- approximately double the magnitude of the decrease into the distant future
-	Species does not establish
#	Seasonal shift
	Not modelled

Figure 10: The predicted water quality changes because of climate change in selected areas in South Africa (Hughes, et al., 2014)*.

A perspective on water quality futures

To date, substantial research investment has been made in supporting water quality management in South Africa, with clear examples of where such research has made a positive impact. Since its inception, the WRC has played a critical role in supporting the development of water quality management policies and strategies, each mandating the promulgation of different water quality regulations. However, there is a need for a retrospective analysis to assess the impact of past WRC research on overall water quality management in South Africa, with a view to identifying gaps and areas of improvement. Furthermore, water quality issues are becoming more and more complex and diverse. In this era of growing uncertainties, addressing water quality challenges requires new imperatives and approaches that support a shift to more sustainable, integrated, and equitable approaches.

The 'One Water' concept considers the water cycle as a single integrated system, consisting of different sources – surface water, groundwater, stormwater, and wastewater. The quality of these interconnected sources needs to be managed in an integrated manner, considering the different multiple end uses, i.e., domestic, the environment, industrial and agricultural uses, to benefit livelihoods, the environment, and the economy. Thus, the future research focus of the WRC water quality portfolio will be on understanding the influence of major drivers (i.e., climate change, industrialisation, land use/cover, etc), as well as anthropogenic activities, on water quality changes in raw water and treated water sources for different uses including domestic, and agricultural and industrial uses. Research on contaminant sources, transport, and partitioning and as well as their combined impacts will be key in determining appropriate risk management scenarios and developing the appropriate environmental water quality management responses such as tools/technologies and regulatory/policy instruments. Going forward, research on water quality will be addressed under the following programmes.

Programme 1: Smart water quality monitoring and decision making

Programme 1 aims to improve understanding on the economic and global change (climate change, land use/cover, urbanisation) drivers, as well as consequent pressures and uses (drinking, industrial and agricultural uses) that contribute to the deterioration of water quality within the ecosystem. This programme is also aimed at fostering an understanding of the sources, transport, and partitioning of contaminants between the water component and sediment. This programme supports research on the development of innovative methods for detection, monitoring and the subsequent use of the information for decision making. This encompasses data acquisition, use of innovative information communication technologies and models for real-time monitoring, as well as predicting and forecasting water quality; development of knowledge hubs and cataloguing platforms for knowledge dissemination and subsequent use of the information for decision-making.

Programme 2: Water quality regulation, compliance, and reporting

Research under this programme is aimed at strengthening the implementation of a smart and integrated water quality management approach, where the water cycle is considered as a single integrated system, consisting of different interconnected sources whose quality must be managed in an integrated manner, considering the different multiple end uses, i.e., drinking, environmental use (Reserve), industrial and agricultural uses. Research supported under this programme includes development of customised regulations and standards by presenting good practice related to water quality risk management and surveillance, and by providing health-based targets. In addition, research on the development and implementation of innovative solutions and responses for water quality management will be supported.

Programme 3: Risk assessment for environmental water quality management

Research in this programme will focus on assessing the risks and impacts of water pollution on sustainable development. Specific focus areas include selection of indicators and biomarkers for assessing the cost/benefit of water pollution on human health, ecosystem, and the economy. With regards to human and environmental health, studies aimed at researching and assessing water quality risks because of non-point and point pollution to both human and ecological systems are encouraged. Risk analysis that will be sought after in this programme include, both quantitative and comparative risk assessment, integrated human and ecological risk, risk perception/communication as well as epidemiological studies and animal to human extrapolation. All risk analysis that are conducted in this programme should be meaningful in terms of having an impact on either assessment, communication, or management (real time or predictive).

Programme 4: Emerging issues and substances of concern in water

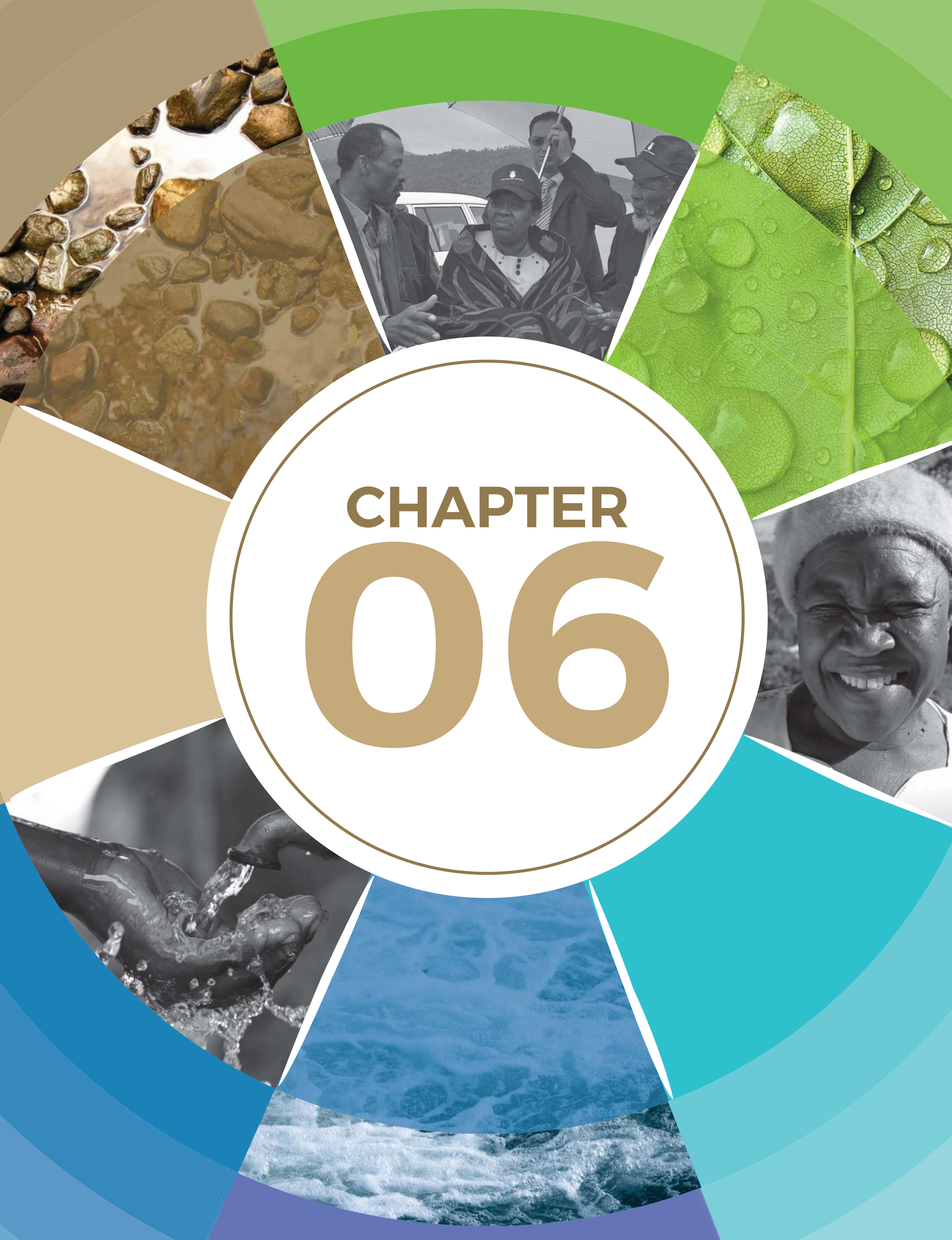
The specific research focus for programme 4 is on tracking the emergence of new water quality issues and substances of concern considering the three types of emerging waterborne pollutants: (1) emerging chemicals of concern deposited from the atmosphere, (2) emerging chemicals of concern from wastewaters, and (3) microbes that are either newly discovered pathogens or long-established agents recently rendered more resistant and/or virulent. Research supported under this theme involves the integration of state-of-the-art analytical and environmental forensic technologies for studying the sources, concentrations, transport, and fate of these substances within the aquatic ecosystem. In addition, research on the development and application of environmental toxicology techniques for determining the health effects of these emerging substances on humans and the ecosystem.

Programme 5: Innovations in water treatment technologies

This programme is aimed at supporting the development and demonstration of innovative water treatment technologies for addressing both the traditional and emerging threats to water resources. Research supported under this programme includes the development and demonstration of innovative technological solutions for drinking water purification (both municipal and household), desalination of seawater or brackish water, as well as in situ water treatment technologies for environmental remediation. Technology demonstrations supported under this programme should clearly demonstrate primary linkages and trade-offs between energy use efficiency (and cost), and related water supply implications and water quality goals, as well as linkages to better outcomes in terms of health, livelihoods, and economic gains.

Although information presented in this Chapter suggests that considerable improvements have been made thus far in water quality management, further research investments on water quality are still necessary for a more balanced and multidimensional approach to policymaking, governance, operations, and management of the quality of the limited water resources.

CHAPTER 06



WATER LAW AND THE WATER RESEARCH COMMISSION – TOWARDS THE GOAL OF WATER FOR ALL FOR EVER

John Dini, Melandri Steenkamp, Carolyn Palmer and Dhesigen Naidoo

INTRODUCTION

The advent of democracy in South Africa in 1994 set in motion a fundamental overhaul of the policy and legal frameworks pertaining to water. The post-apartheid Constitution adopted in 1996 ushered in a new system of intergovernmental relations, along with the articulation of human rights regarding access to water and environmental protection, and imperatives for redress of the effects of past racial discrimination. This, in turn, served as a major driving force for the development of new national water policy, in the form of the 1997 White Paper on a National Water Policy, and its legislative instruments, the 1997 Water Services Act and the 1998 National Water Act.

Arising from a specific historical context and rooted within a broader political transition, these three documents collectively represented a radical paradigm shift from previous approaches to the management of water in South Africa. This created specific and substantial demands for relevant, credible knowledge to guide the drafting teams in crafting legislation that drew from both international experience and home-grown solutions, and able to respond appropriately to the unique realities of water in post-1994 South Africa.

The Water Research Commission (WRC) was well-positioned to respond in several ways to the demand for applicable knowledge in support of the water law reform process. These included commissioning new research to address specific emerging questions, in addition to existing WRC-funded research that proved applicable to the challenges of law reform. The government of Finland provided additional funding for researchers supported by WRC projects to extend their work and inform the drafting of the legislation.

Figure 1. Voters queue to vote in the first South African democratic elections in 1994 (Credit: Commonwealth Secretariat)

This chapter explores the theme in more detail, by examining the contribution made by the WRC to the processes that ultimately led to the adoption of the White Paper, Water Services Act and National Water Act, and subsequent research to support their implementation. This narrative is contextualised through an initial discussion of the challenges confronting those who were tasked with the overhaul of water policy and law during the term of the first democratic administration. This leads to an examination of the contribution made by the WRC to these processes, including an analysis of relevant research projects and other forms of support. Particular attention is given to the role of the WRC in supporting the scientific community to lay the foundations for the legislation of environmental water requirements through the National Water Act. Although the chapter concentrates on national legislation, it also briefly examines the WRC contribution to water-related aspects of international law. The chapter concludes with a discussion of the contemporary critiques of our water legislation and their implications, among others, for future programmes of WRC-funded work relevant to water law. It is beyond the scope of this chapter to examine the contribution of WRC-funded research to the development and implementation of environmental law, in the form of the National Environmental Management Act and its subsidiaries. This is dealt with in Chapter 8.

The historical challenge

The challenge to the new democracy in 1994 cannot be overstated. The lead liberation organisation – the African National Congress – became the governing party under President Mandela and took on the task of building the foundations of a democracy based on universal suffrage on the one hand, and servicing the needs of all South Africans on the other. The extent of the challenge was extreme on both fronts.

Embedded inequalities reflected in water

Water starkly reflected the race-based inequalities that characterised the apartheid dispensation. In 1994, of a total population of 40,6 million, it was estimated that 14 million people did not have access to adequate water supply services (reliable, sufficient, clean water for basic needs) and 21 million lacked adequate sanitation (DWAF, 2004). Black African households comprised a disproportionately high component of those lacking access to these basic services (Hirschowitz and Orkin, 1997). The water legislation in place at the time of the transition to democracy made no provision for universal access to water for basic human needs (Stein, 2005).

Figure 2. Access to basic water supply has been, and remains, a challenge in many rural areas. Women and girls often carry most of the burden for water collection. (Credit: WRC archives)

The 1956 Water Act, the predominant piece of water legislation at the time of transition to democracy, embedded a system of riparian rights that governed the use of water for productive purposes such as irrigated agriculture, mining and manufacturing. Under the colonial and apartheid regimes, riparian rights inextricably linked water-use rights to land ownership and access (Stein, 2005). The systematic dispossession of black people of their land through a range of legislative measures, including the 1913 Land Act and various urban interventions like the Group Areas Act, meant that racially determined inequalities in land ownership were mirrored in access to water for productive purposes. As a result, 1,2% of the population controlled 95% of the water used in rural areas, hence also determining the flow of economic benefits from the use of such water (van Koppen and Schreiner, 2014). It has been argued that there has been, and continues to be, greater inequality in access to water than in access to land (Woodhouse, 2008).

A new Constitution

The Constitution defines the heart of the democratic Republic of South Africa. The interim Constitution of 1993 that guided the country to its first democratic elections was replaced by the Constitution of South Africa in 1996, promulgated by President Mandela on 18th December of that year. The Constitution in turn became the guiding framework and the boundary condition for all law and policy in the new democratic state. It was against this backdrop that water policy and law in the new democratic state was conceived.

The Bill of Rights embedded within the Constitution affirms that everyone has the right to have access to sufficient water, and to have the environment protected for the benefit of present and future generations. Responsibility is placed on the state to take reasonable measures, within its available resources, to progressively realise these rights. South Africa is one of 39 countries (or 20% of countries worldwide) that explicitly recognise the human right to water in their constitutions (Jung et al., 2014).

Figure 3. The doors of the Constitutional Court doors are inscribed with the rights enshrined in the Bill of Rights. (Credit: Melandri Steenkamp)

The new statutory regime for water comprised one of the first sectoral translations into law of the spirit of the new Constitution and laid enabling legislative foundations for the achievement of aspects of the goals of the Reconstruction and Development Programme (RDP). The RDP embodied the vision and plans by which the post-apartheid government would orientate its activities towards addressing the poverty and inequality evident in almost all aspects of South African society, while placing the economy on a path of high and sustainable growth (Office of the President, 1994).

Water law reform

Recognising the urgent need to reform the country's water law, the late Prof Kader Asmal, the first post-1994 Minister of Water Affairs and Forestry, initiated a law-reform process. While the immense, urgent challenges of equity and redress were front of mind, they were by no means the only reason for embarking on such a fundamental overhaul. It was also becoming clear that the 1956 Act was no longer up to the task of sustainably managing a scarce and variable resource within the context of a modern industrial economy and increasing, competing demands for water (Water Law Review Panel, 1996). This realisation was summarised with characteristic candour by Prof. Asmal: "Along with most of the rest of the world, South Africa's approach to water management was also technocratic in nature, inward-looking in terms of the disciplines necessary to make informed decisions, and seemingly obsessed with building monuments to engineering prowess. It was an age when supply-side management was king (and I use the sexist term deliberately); an age, I suspect, when the notion of integrated water resource management was seen as a communist plot!" (Asmal, 2008, p. 663).

The combination of these driving forces saw water being accorded priority by the first democratic administration, resulting in dramatic changes to the water policy and legal frameworks. The first step in the process entailed the publication of a document titled You and Your Water Rights (DWAF, 1995) that examined the problems with the existing water law and solicited ideas for potential solutions. Public responses were synthesised and presented to the Water Law Review Panel. The responses included an input, co-ordinated by the Southern African Society for Aquatic Scientists (SASAqS), that became influential in advocating for the protection of aquatic ecosystems. The Water Law Review Panel developed a set of Water Law Principles (DWAF, 1996) that would underpin the drafting of new legislation. After approval by Cabinet in 1996, the principles informed the drafting of the White Paper on a National Water Policy for South Africa (DWAF, 1997). The process culminated in the National Water Act (36 of 1998), which provided for the protection, use, development, conservation, management and control of the nation's water resources.

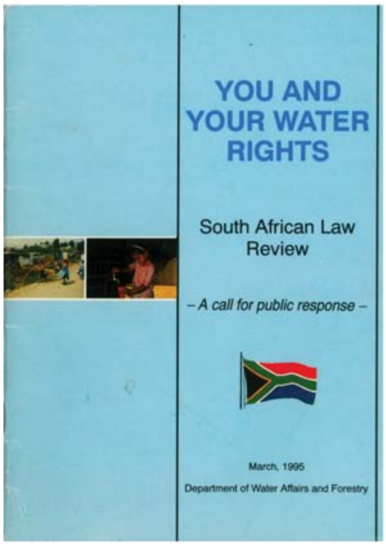


Figure 4. The booklet, You and Your Water Rights, published during the South African water law review in 1995. (Credit: WRC archives)

The National Water Act was drafted as the overarching legislative framework for water. However, at the time of drafting, it was argued that water services issues were too urgent to wait for the promulgation of the National Water Act, and the Water Services Act (108 of 1997) was promulgated a year earlier. Developed from the foundation of the ***White Paper on Water Supply and Sanitation Policy*** (DWAF, 1994), the Water Services Act deals with matters concerning the provision of water services and sanitation. Together, these Acts constitute the two primary contemporary water laws in South Africa. Although separate statutes, they are interrelated, with the interpretation of the Water Services Act subject to the National Water Act (Stein, 2005). This crucial interconnectedness is, however, habitually overlooked.

A radical departure from their predecessors, the National Water Act and Water Services Act repealed and replaced the body of water law inherited from the colonial and apartheid past. Their far-reaching reforms were primarily enabled by the wider context of political transition in the country (Muller, 2012). This specific historical context, characterised primarily by the democratic transition and articulation of the desired socio-economic changes to the fabric of South African society, resulted in a formulation that reflected the dominant discourses and struggles in both the Constitution and the

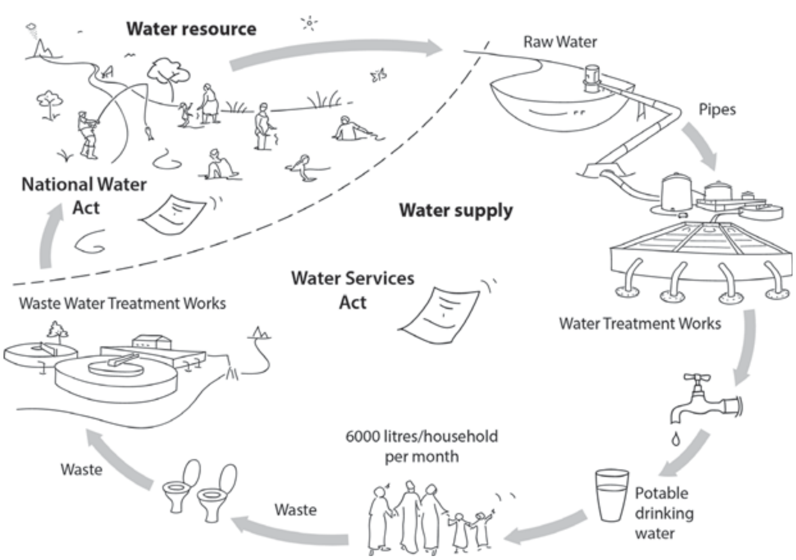


Figure 5. Designed to operate in concert, the National Water Act and Water Services Act collectively cover the entire water value chain. Source: Palmer (2018)

process to formulate water policy (Chikozho, et al., 2018). At the time, the National Water Act was celebrated as a global pioneer and became a trendsetter for a new wave of water-sector reform in several countries, including Mexico, China and Zambia (Woodhouse, 2008; Schreiner, 2014). Minister Asmal was awarded honorary doctorates by several South African universities, and became the first non-scientist to be awarded the prestigious Stockholm Water Prize in 2000, based on his work in developing the Act (SIWI, 2000).

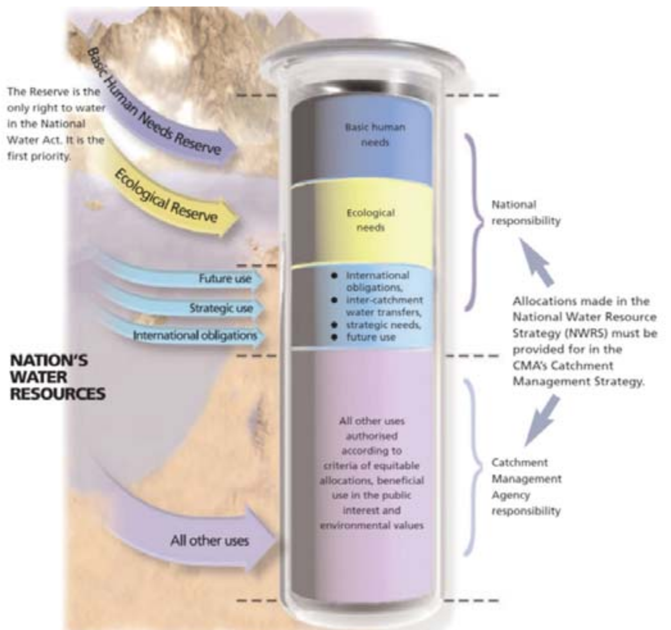


Figure 6. The hierarchy of priorities established by the National Water Act for the allocation of water. Source: DWAF (n.d.)

Through the adoption of the public trust doctrine, the National Water Act removed the concepts of access to water by virtue of land ownership, and private water, and placed ownership of water in the hands of the people of South Africa, held in trust by the state (Stein, 2005). The Act gave effect to aspects of constitutionally enshrined human rights to access to water, and a healthy environment, by embedding equity and sustainability as central guiding principles in how all decisions are made about water. A key mechanism for doing this was the concept of the Reserve: the setting aside, before any other use, of sufficient water for basic human needs and for sustained functioning of the ecosystems that inseparably underpin the water-resource base. South Africa was the first country to legislate this environmental right to water (Asmal, 2008). A system of water-use licencing was introduced for regulating water uses (defined broadly to include taking and storing water, streamflow reducing activities, waste discharges and other activities that may impact on a water resource) above certain thresholds. Licencing was positioned as one of the primary mechanisms for enabling re-allocation of water to give effect to imperatives for equity and redress. The National Water Act expressed the principle of subsidiarity by establishing new institutions, in the form of Catchment Management Agencies, to decentralise the management of water resources to the lowest appropriate level. The Water Services Act reflected this principle through its elaboration of the Constitutional assignment of water services provision to local government level.

Water-use rights endowed by the 1956 Water Act were retained under the new dispensation in the form of existing lawful uses (ELU). These are water uses that were authorised by the 1956 Water Act or that were permissible under any other law in force immediately before the commencement of the National Water Act (Stein, 2005). The provision for ELU was intended to be a transitional measure to allow people using water legally, prior to the National Water Act coming into effect, to continue using this water without having to immediately apply for a water use licence (DWAF, n.d.).

The team of lawyers and water experts tasked by Minister Asmal with reforming water policy and legislation faced deep and broad challenges. The process reflected many of the original ideological fault lines, vested interests in maintaining the status quo, mistrust, compromise and sense of possibility that characterised the drafting of the Constitution (Schreiner, 2014; Chikozho, et al., 2018). The process reflected the political and economic forces at play, not least the influence of advocates of neoliberal economic thinking, including the argument of water as a commodity (Bond, 2014) and those wishing to retain the racially-slanted status quo in relation to existing rights to use water (Movik, 2012). The contestations that characterised the water law review process contributed to the demand for relevant, credible knowledge to inform the choices being made by the drafting team. The loss of confidence by the Minister in some of his own senior technocrats, regarding their commitment to transformation (Ashton et al., 2012*), made the need for such knowledge all the more critical. The WRC proved to be a trusted knowledge repository with the required degree of legitimacy to act as a convener for mobilising researchers and knowledge resources in the service of the legislative task at hand.

WRC contribution

This section describes the support that the WRC provided during the law review process that led to the drafting of the National Water Act. It also considers subsequent research undertaken since the adoption of the Act in 1998, aimed at supporting the implementation and further development of water law. Emphasis is placed on retracing the role of the WRC in enabling the legislation of environmental water requirements through the National Water Act.

Environmental water requirements

Chapter 3 of the National Water Act sets out a series of measures intended to ensure the protection of all water resources. At the time of its writing, this chapter was globally acclaimed for its explicit recognition that water resources are more than just water, that aquatic ecosystems comprise the resource base on which all other uses depend, and that healthy ecosystems underpin the sustainability of water use (Rowlston, 2011*). The chapter contains three sets of Resource Directed Measures to protect aquatic ecosystems to secure ecologically sustainable development and use of water resources. 1) A system for classifying water resources (rivers, springs, wetlands, lakes, surface water, estuaries, and aquifers) into management classes that determine the balance between the use and protection of individual water resources. 2) The Ecological Reserve describes the pattern, quantity and quality of water required to maintain the functioning of aquatic ecosystems. 3) Resource Quality Objectives describe and quantify the quantity and quality of water, assurance of instream flow, and character and condition of instream and riparian habitat and biota. The Resource Directed Measures are also discussed in the section on Instream Flow Requirements in Chapter 8 of this book.

The inclusion of these elements in the National Water Act was a huge paradigm shift from its predecessor – the notion of sustainability was completely absent in the 1956 Water Act. Reflective of international and national debates under way at the time, sustainability featured strongly in the Water Law Principles (DWAF, 1996) and subsequent White Paper on a National Water Policy for South Africa (DWAF, 1997). The challenge facing the advocates of these principles and the legal drafters was to convert the underlying intent into legislative tools. At each stage of the process, it was necessary to present cogent scientific arguments to justify the legislation of these aspects, as well as how they would be translated into law (Palmer, 1999). The inclusion of a WRC-funded researcher, Tally Palmer, as deputy chair of the Water Law Review Panel proved key to bridging the flow of innovative thinking and recent research results into law (Ashton et al., 2012*).

Funding from the Finnish government to the Water Law Review Panel enabled WRC resources to be stretched further to ensure a flow of current, relevant knowledge into the law-review process. The Finnish resources were concentrated on supporting further development of new, transformative concepts such as the Reserve, and securing legal opinion on de-linking water and property rights. Some of the funds were channelled to the WRC, supporting researchers with current WRC projects to extend their work to inform and engage with the legal drafting team (e.g. Tharme and King, 1998*).

This enabled emerging South African methods for determining environmental flows, underpinned by the pioneering work of scientists like Jackie King and Jay O'Keefe (e.g. King and Tharme, 1994*; and King et al., 1996*), to be championed by Tally Palmer in the law review process (Ashton et al., 2012*). It was partly for this work that Jackie King, herself a beneficiary of WRC funding over the years, received the 2019 Stockholm Water Prize (SIWI, 2019). Foundational research on the classification of rivers (e.g. O'Keeffe et al., 1994*) provided the scientific underpinnings for the inclusion of management classes in the suite of Resource Directed Measures. Subsequent WRC funding supported the development of water quality components for inclusion in environmental flows methods (Palmer et al., 2005). A WRC-published book, Sustainable use of South Africa's inland waters: A situation assessment of Resource Directed Measures 12 years after the 1998 National Water Act edited by King and Pienaar (2011a*), provides a detailed account of the foundational research that enabled environmental flows to be incorporated into law, as well as reflecting on the first 12 years of implementation once the Act came into effect.

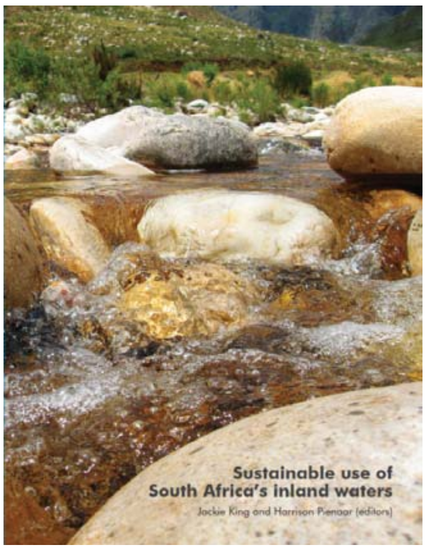


Figure 7. The book, Sustainable use of South Africa's inland waters, provides a detailed account of the developments that allowed for the inclusion of environmental flows in South African water law.

While the required knowledge stemmed from a combination of research funded by the WRC and other sources, Ashton et al. (2012*) describe the repository role of the WRC for innovative research on environmental flows as one of the factors enabling science to become a powerful driving force in the water-law review process. These arrangements brought into the process a decade's worth of research into environmental flows, including the outputs of the highly successful Kruger National Park Rivers Research Programme managed by the WRC (see final programme report to WRC by Breen et al., 2000*). Exchanges with international experts, focussing on technical aspects of the law review process, were facilitated and funded by the WRC. In the view of Biggs et al., (2008), this illustrated the value of the slow and steady building of knowledge and relationships, coupled with seizing the window of opportunity created by the democratic transition, to inject sustainability into South Africa's water law.

The nature of the process, with legislation as its ultimate output, required deep integration between the disciplines of hydrology, hydraulics and biology, and their respective communities of practice. Water lawyers involved in the process, notably Advocate François Junod, played a key role in engaging with the scientific community of practice to ascertain whether the science was sufficiently robust to substantiate the legislation of environmental water requirements. His endorsement of the methodology as legally defensible, together with the legal opinion funded by the Finnish government, provided the necessary confidence to include the Reserve, and a system of administrative water-use licensing, in the National Water Act.

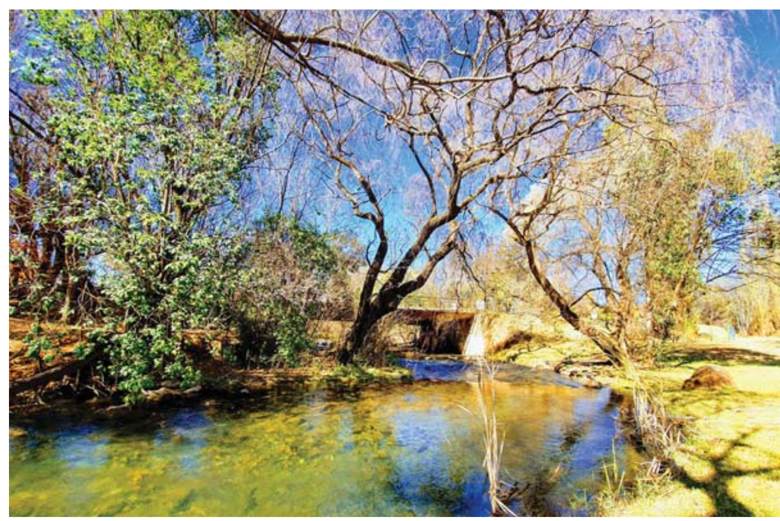


Figure 8. South Africa was one of the first countries in the world to include environmental water requirements in its water legislation. (Credit: Melandri Steenkamp

Implementing water law

To further assess the extent and effectiveness of the implementation of the National Water Act, the WRC published several reports dealing with the law and policy development process. De Coning and Sherwill (2004*) provide a recording and interpretation of the water policy process followed by the government between 1994 and 2003. They endeavoured to disclose lessons of experience and suggest findings regarding the various policy, implementation and evaluation arrangements that still needed to be put in place to ensure the sustainability of the policy. Moreover, this report noted that the future of the policy depended on the ability of structures other than the then Department of Water Affairs and Forestry (now Water and Sanitation, DWS) to assume the appropriate powers and functions to allow the Department to play a regulatory and policy coordinating role (De Coning and Sherwill, 2004, p.31*). All things considered, the report presents the view that economic and financial analysis could have been improved during the policy process and that more systematic planning may have improved the quality of the policy process.

Following on this, Roux et al. (2006*) recommended that improving the quality of the development and implementation of water and related policy in South Africa would involve a proper understanding of the inter-dependency between policy implementation and institutional development. This makes understanding institution-building vital to approaching cooperative government and governance in water, intergovernmental relations and coordination, human resource development and financial viability of various institutional architectures.

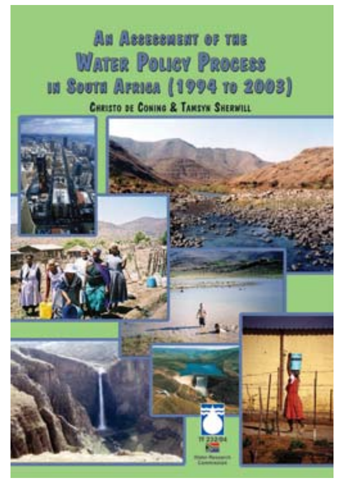


Figure 9. De Coning and Sherwill (2004) analysed macro policy developments in water between 1994 and 2003.

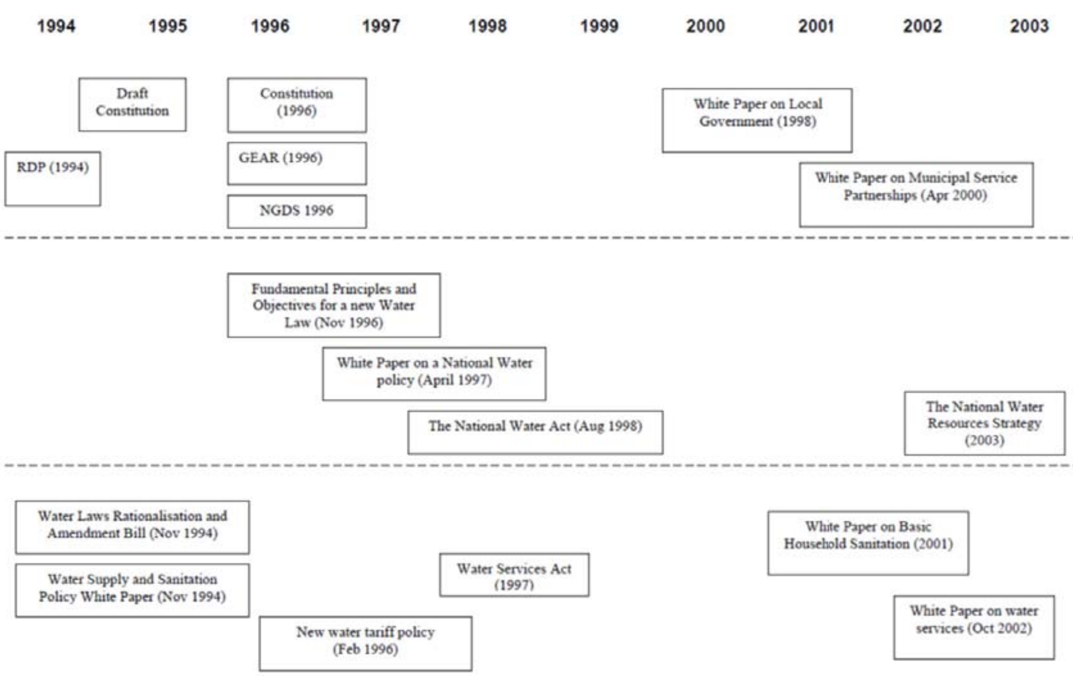


Figure 10. The South African water legislation development process.

The National Water Act offers many water-resource regulatory instruments, yet arguments persist that these are not being used effectively to address the country's water resource challenges. The selection of the appropriate tools and the development of regulatory policy can be very challenging. Understanding this complexity and the competing interests that are involved will help regulators to avoid making the wrong decisions and undermining the intended policy outcomes. Schreiner et al. (2011*) argue that there is a need for more research on how water resources regulatory tools can support sustainable economic growth, and race and gender transformation in South Africa. The report works toward the development of an effective framework for regulating water resources in the country, through assessing international good practice in the technical regulation of water resources, and examining appropriate tools for achieving effective regulation. It is argued that South Africa lacks the necessary capacity and information to properly implement its existing water resources regulatory frameworks. The authors point to the failure of regulatory instruments, like water use licensing, amongst other things, in adequately addressing water resource challenges such as deteriorating raw water quality and high levels of water theft (Schreiner et al., 2011, p. 25*).

Figure 11. The Katse Dam forms part of one of Africa's largest water transfer schemes, the Lesotho Highlands Water Project between Lesotho and South Africa. (Credit: Skypixels)

Speaking to environmental protection, and by extension aquatic ecosystems, Uys (2006*) critically reviews the various tools and institutions that support the use and development of natural resources for sustainability. She argues that the National Water Resource Strategy (NWRS), the legally binding framework for facilitating water resource management, is sophisticated and encompassing, making it a key management tool to be enhanced and developed towards integrated resource management (Uys, 2006, p. 27*). Since the publication of the report, the NWRS has been updated and the second edition published in 2013 (NWRS2, DWA, 2013). The NWRS2 elaborates on the vision of the National Water Act, through its focus on improving the implementation of policies and procedures to address the environmental values associated with water. The report adds to an important discourse on the integration of environmental management systems and coordinated environmental governance, which sees South African water law as an important instrument for the integrated management of natural resources.

Subsequent reports, such as Wilkinson et al. (2018*), identified gaps and constraints in water resources and water services law and policy. The report indicates that the NWRS2 has the potential to address the challenges of water scarcity by developing policies that support education in, and the wise use of, water. Water conservation and demand management are expected to become integral components of the country's water management policies. The report benchmarked South African policies against those of other countries such as Swaziland, Botswana, Namibia and India, making the findings and analyses significant beyond South Africa.

Other WRC projects have approached water law from the perspective of legal practitioners and researchers. ***Water Law of South Africa 1912-1998 by Uys*** (2008*) presents a comprehensive set of court cases that dealt with South African water law as codified primarily through the 1912 Irrigation Act and the 1956 Water Act. This compendium of case law was designed as a legal source to support the implementation of the 1998 National Water Act. A subsequent report, derived from post-1998 case law and literature, provides scholars, law practitioners and policymakers with an inventory of legal questions and potential legal issues brought up during the first decade of the implementation of the 1998 National Water Act (Uys, 2009*). The report identifies and consolidates the legal issues and makes recommendations on how these may be better addressed in the foreseeable future. Some of the suggestions include defining and delineating the concepts of equitable water resources management to avoid a deadlock that could arise when the decisions being made are not balanced, hence placing the onus on decision-makers to provide meaning to the concept (Uys, 2009, p. 17*).

The public trust doctrine has significantly influenced the law of property in South Africa and has contributed to a challenging of the concepts of ownership and property in South African jurisprudence. Van der Schyff (2011*) analyses the effect of the public trust doctrine on the responsibilities and obligations of role players in decentralised water resources management. The report assesses the most pertinent legal incorporation of the concept, as well as indicating how the doctrine can best be used to balance the demands on water resources and support water reforms aimed at addressing the legacy of gender and racial discrimination. She asserts that the state's trusteeship of water resources does not diminish the public's collective responsibility to manage and protect the nation's water resources sustainably and equitably (Van der Schyff, 2011, p. 79*).

Recognising that the water sector was the focus of one of the first major sectoral policy overhauls of the post-1994 era, the WRC commissioned a legal history study to document and analyse the process that led to the formulation of the National Water Act. The report by Chikozho et al. (2018*) contains a compendium of over 300 documents, including minutes, submissions, correspondence, reports and scholarly articles relating to the water law review process. This renders it a useful reference point for revisiting the extent to which the policy development and law reform processes that characterised the immediate post-1994 period achieved the desired outcomes. Further, it provides an opportunity to extract lessons to guide the water sector and beyond in tackling the unresolved challenges of the democratic era.

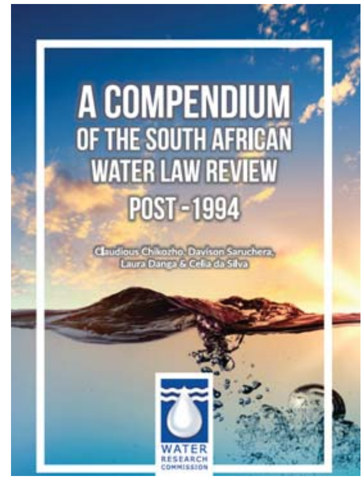


Figure 12. The Compendium of the South African water law review post-1994 contains more than 300 documents related to the water law review process.

Water law in a transboundary context

The National Water Act is one of the few national water laws that make provision for the allocation of water to neighbouring countries with which watercourses are shared (Thompson, 2006, p. 380). South Africa shares the Maputo, Incomati, Limpopo and Orange rivers with its neighbours. In the first study of its kind in South Africa, Turton et al. (2004*) examined the hydropolitical history of these international river basins to contextualise current patterns of conflict and cooperation between the riparian countries and anticipate potential future trends. South Africa is now a party to a wide range of international agreements on issues related to freshwater management, including transboundary agreements for shared river basins. These instruments have become woven into the country's hydropolitical fabric and have taken on greater economic and political significance as the exploitation of water resources within shared river basins has increased (Turton et al., 2004, p.392*).

Figure 13. The Orange River, which is shared by Botswana, Namibia, Lesotho and South Africa.

While international agreements and laws can be difficult to enforce, they still capture internationally accepted principles and objectives that South Africa is obliged to implement once it becomes a signatory. The latter were addressed in a comprehensive WRC report by Ashton et al. (2006*), highlighting the evolution of South Africa's international relations concerning water. The report aims to improve the management of shared watercourses by making available copies of all the relevant international agreements and arrangements that South Africa has entered into regarding the management of water. Besides presenting the complete set of agreements in a single, accessible database, the authors intend that their analysis can serve as a resource for future international negotiations on water resource management (Ashton et al., 2006, p. 20*).

Challenges in implementation

We now have the benefit of more than two decades of hindsight in giving effect to the aspirations of the drafters of the Water Services Act and National Water Act. The process of developing the legislation, contested as it was, and the resulting end products, gave rise to a sense of alignment between the mandate for change encapsulated in the RDP and the Acts as instruments for effecting the desired change in the water sector. Although tempered by the magnitude of the challenges faced, a tremendous sense of possibility and optimism surrounded the policy development and law reform processes in the water sector during the term (1994-1999) of the first democratic administration. The outcome of these processes was a set of legal instruments that appeared to provide the necessary enablers for the desired outcomes expressed in policy to be realised.

The reality has proven to be quite different, however, as the magnitude of continuing challenges in the water sector attests. In hindsight, this is perhaps unsurprising, given the persistence of the colonial and apartheid legacy across all facets of South African society. The water sector is not an exception to the trend described by Modiri (2018) of dissipation of much of the optimism concerning the promises of a new legal and political order that characterised the immediate pre- and post-1994 era. Research undertaken by the WRC, once the legislation came into effect in the late 1990s, switched to supporting its implementation and examining the extent to which the desired changes were being realised.

The period between the National Water Act coming into force in 1998 and the present has exposed several substantive challenges in realising its encapsulated vision. Existing Lawful Uses remain in place and continue to perpetuate the unjust allocation of water, despite this provision being included in the National Water Act as a transitional measure. Many of the Irrigation Boards established under the 1956 Water Act have not been dis-established or converted to Water User Associations (regulated under the National Water Act) within six months of the Act coming into effect, as originally intended. Extremely slow progress has been made in establishing Catchment Management Agencies, with only two currently operational.

The science required to determine the Resource Directed Measures is perceived by some as being too complex, and their implementation too costly (King and Pienaar, 2011b*). While huge progress has been made in streamlining and process (O'Keeffe et al., 2002), research funded by the WRC has contributed to identifying the challenges that remain and potential solutions (e.g. King and Pienaar, 2011a*; Pollard and du Toit, 2011*). Partly as a result of these challenges, the overall ecological condition of South African rivers has declined during the period 1999 to 2011 (Nel and Driver, 2015).

When the Act came into effect, at least 95% of the authorised volumes of water for irrigation was used by large-scale farmers, most of whom were white (Schreiner and van Koppen, 2002). The inequalities embedded in the form of Existing Lawful Use have proven to date to be anything but transitional. Water allocation reform has not come close to meeting the Water Allocation Reform Strategy targets that 45% of allocable water should be allocated to black people by 2019 and 60% by 2024 (DWAF, 2008). The status quo remains largely intact, with water use rights still overwhelmingly vested with white, large-scale commercial water users (Pegasys Institute, 2019).

Systemic transformation at the scale of South Africa's democratic transition was intrinsically complex and unintended consequences were inevitable. Separation of land ownership and rights to water use was necessary for equity, but the administrative task of replacing a simple allocation mechanism was enormous, and the consequent delays were an impediment to the realisation of many of the hoped-for reform outcomes.

The slow progress in re-allocation of water has been attributed to several factors. With all available water resources in many catchments already being fully allocated to existing users, little available water exists for allocation to new entrants (Reddy et al., 2020*). Provisions in the Act for compulsory licencing, through which holders of Existing Lawful Uses are required to apply to convert these old-order entitlements to water use licences under the National Water Act, have only recently been initiated in a small number of catchments covering very small areas of the country (Kidd, 2016). This is the primary mechanism through which water in fully allocated catchments would be freed up for re-allocation for purposes of redress, but is proving to be time-consuming and complex to implement (Kidd 2016.). It has been argued that the reluctance of the Department of Water and Sanitation to activate these mechanisms has been driven in part by perceptions that economic and environmental damage may result from the transfer of water from established users, such as mines and commercial farmers, to emerging users (Funke and Jacobs, 2011).

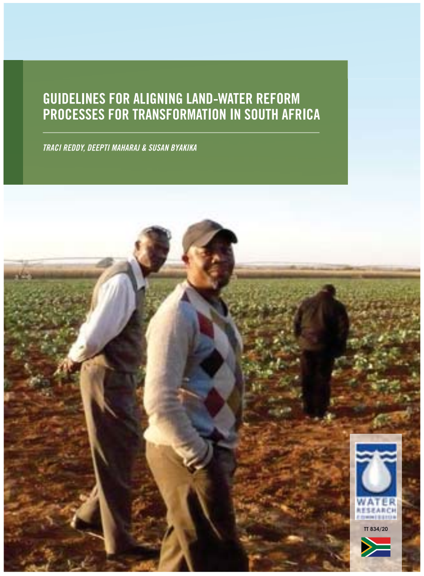


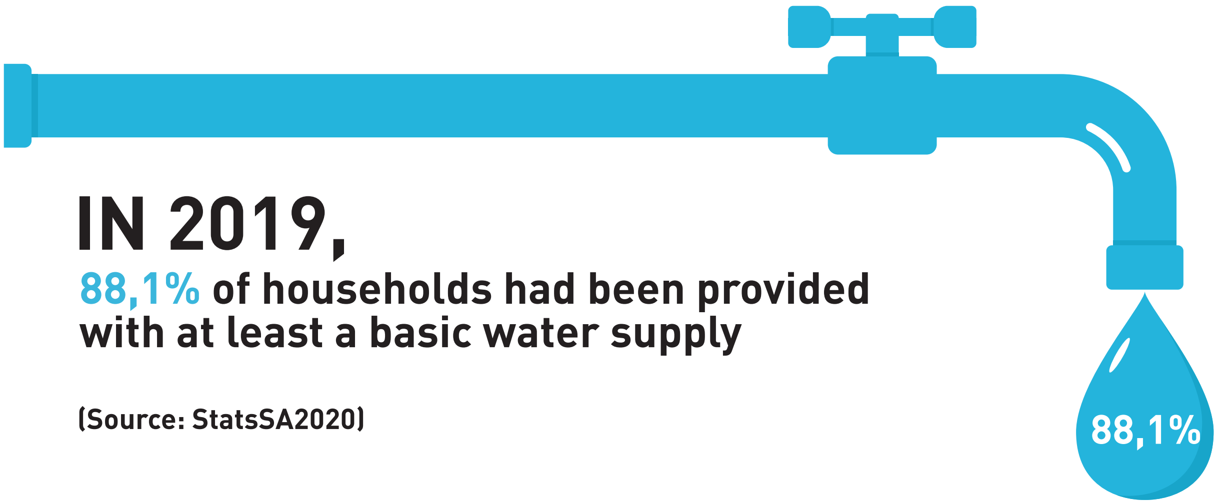
Figure 14. Opportunities have been identified for improving integration between land reform and water reform, leading to better developmental outcomes (Reddy et al., 2020).

Recent WRC-funded research has highlighted how the lack of coordination between land reform and water reform further exacerbates the lack of progress in re-allocating water (Reddy et al., 2020*). Although the National Water Act has uncoupled water use rights from ownership or control of land, in practice it is implausible to apply for water for productive use without having access to land on which to exercise the use of this water (Kidd, 2016).

Implementation of the sections of the National Water Act dealing with water-use licencing has also proved difficult and problematic, entailing complex, time-consuming and costly application procedures that have resulted in significant backlogs in the issuing of licences (van Koppen and Schreiner, 2014). Emerging users have reported experiencing the bureaucracy as difficult to access and non-responsive for securing information and support on requirements for water use authorization (Williams, 2018*). This contrasts with the experience of established users who can rely on support from institutions such as Water User Associations or pay for the services of skilled consultants to mediate on their behalf. There remain significant human and financial capacity constraints in government to efficiently process water license applications, adding to the problem (Reddy et al., 2020*).

In many respects, the current contestations around the National Water Act are mirrored in the fault lines that have emerged around the Constitution. The Act continues to be defended as a progressive legal instrument for driving the vision for change articulated in a carefully crafted and extensively consulted water policy framework, which in turn reflected the vision expressed through the RDP for post-apartheid South Africa (Muller et al., 2018). At the same time, a critique is emerging of the National Water Act as an enabler for continued high levels of inequality in the water sector. The application, through a WRC-funded project, of a decoloniality lens to the National Water Act has produced a perspective that labels elements of the Act as colonial agendas repackaged and well disguised as progressive global good practices (Hydrosoft Institute, 2021*).

Regarding water services, the Water Services Act established a system of Water Service Authorities (WSAs), in the form of municipalities that have primary responsibility for ensuring access to water and sanitation services. There are currently 169 metropolitan, district and local municipalities designated as WSAs. The most recent, available data indicate that, in 2019, 88,1% of households had been provided with at least a basic water supply: 44,9% of households had access to piped water in their dwelling, 28,5% had access to piped water in their yard, 12,2% relied on communal taps and 2,5% relied on neighbours' taps (Stats SA, 2020). While significant progress has been made since 1994 in providing water and sanitation to people who previously lacked access to these services, difficulties have been identified in the ability of many WSAs to consistently provide these services to the required minimum standards. When minimum standards for reliability are considered (interruptions of less than 48 hours at any one time and a cumulative interruption time of fewer than 15 days in a three-month period (DWAF, 2003)), the percentage of households served drops to 74% (DWS, 2019). Approximately 56% of the country's municipal wastewater treatment works and 44% of the water treatment works are in poor or critical condition and in need of urgent rehabilitation and skilled operators (DWS, 2018a).



IN 2019,

88,1% of households had been provided with at least a basic water supply

(Source: StatsSA2020)

It is clear that challenges remain in the ability of government to fulfil its responsibility regarding the right to access to water enshrined in the Constitution. One of the consequences of the current legal framework and institutional arrangements is a degree of overlap, potential conflicts with the subsequent suite of legislation that prescribes how local government will go about its business, and lack of agreement on roles and responsibilities (Malzbender et al., 2009, p. 50*). Some WSAs have now been in place for over 15 years and clear signals have emerged that the WSA model requires revisiting. Systemic factors influencing WSA performance have been identified and long-term trends have emerged. Linkages to broader governance and financing challenges facing local governments across the country have been made. A case has been made that the regulation of water services and water resources by separate policies and pieces of legislation, and the resultant development of management tools that are distinct and partly separated from each other, has resulted in the concept of integrated water resource management not being embraced in the broader sense (Jeleni et al., 2011*).

Going forward

The National Water Act and Water Services Act have not undergone a major revision since coming into force in 1998 and 1997 respectively. Processes to amend both Acts are now underway, and these will result in much attention shifting to the substance of water law during the legislative process. The Department of Water and Sanitation has indicated its longer-term intention is to merge the National Water Act and the Water Services Act to form one Water and Sanitation Act (DWS, 2018b). In approaching revision of this legislation, it will be critical for the water sector to paraphrase the question posed by Modiri (2018) in relation to the Constitution, by initiating an honest introspection on whether our current water law has been able to respond adequately to the fundamental contradictions generated by colonisation and apartheid. Such an introspection would need to factor in warnings against the temptation to rewrite the law in an attempt to solve problems that arise not from inherent flaws in the law, but from shortcomings in how it is implemented (Muller, et al., 2018). Being able to distinguish between the two will be critical. In this respect, it is useful to draw on the observation of Davis (2018, p. 7) concerning the Constitution, that polarising the conversation into a 'binary impasse' does not adequately or usefully reflect the complexity of the issue or the very high possibility that elements of both positions may be present at the same time.

Davis (2018) further contends that only by a painfully sustained consideration of history will it be possible to understand the role of law in reproducing the society inherited from the past. Only upon completion of this exercise will it be possible to reimagine a legal system through a process of 'renegotiation' that invites new and alternative perspectives and approaches (Modiri, 2018, p. 297).

Thinking has been done about such alternatives with the National Water Act, even if some are only promising hints of new possibilities at this stage. For example, might the proposed revision of section 25 (the 'property clause') of the Constitution create new options for revision of the National Water Act? The exact nature of the relationship between section 25 of the Constitution and the water rights enshrined in Existing Lawful Use remains to be formally tested in the courts. It appears inevitable that statutory processes for authorising water use will need to be simplified in some way. Unless there is a radical change to the Act, compulsory licensing will continue to be a central mechanism for redress-driven re-allocation of water in catchments that are already fully allocated, but the administrative challenges involved in implementing this mechanism are immense (Kidd, 2016). There may be opportunities to develop specific mechanisms for authorising water use by small-scale users that, for little cost to the user and administrative effort by the regulator, enable progressive realisation of access to water for productive purposes (van Koppen and Schreiner, 2014). Hybrid approaches can also be explored that acknowledge legal pluralism, in the form of both statutory and customary mechanisms for regulating water use. In the process, large numbers of existing small-scale users could be legalised and protected while focusing regulatory attention, in the form of licences, on large volume, high impact users (van Koppen and Schreiner, 2018).

The water sector's experience of law reform in the democratic era amply illustrates the reality that desired changes to the fabric of South African society cannot be brought about simply by legislating for them. Certainly, enabling policy and legislation is necessary but is not sufficient. This raises important questions: if you are investing in change, what needs to be nurtured beyond a change of law? What changes need to be made that better organise for implementation? Important lessons can be extracted from the experience of the WRC and the knowledge generation, capacity building and implementation support it has catalysed on water law and policy.

We suggest that the legislative provision for transformative instruments remains essential for social-ecological justice in South Africa, and that continued and combined research and practice should persevere towards improvement. Effective water resources management, enabling water services provision, is, like most intractable 21^{st} century problems, driven by the complexity of the inextricably linked natural and social systems. Understanding the nature of these complex social-ecological systems, and systems thinking, is essential. The complexity means we need to draw on multiple streams and kinds of knowledge – therefore the emergence of transdisciplinarity has been catalytic. If we need human behaviour to change as a result of understanding, people need to learn together, and experience learning in a particular way, so social learning is a foundation. Methods and processes are needed that enable water managers to translate thinking into action, hence there is a critical need for researchers to understand implementation. These arguments are presented in an accessible form in Palmer et al. (2018*), and the supporting case study research in Palmer and Munnik (2018*).

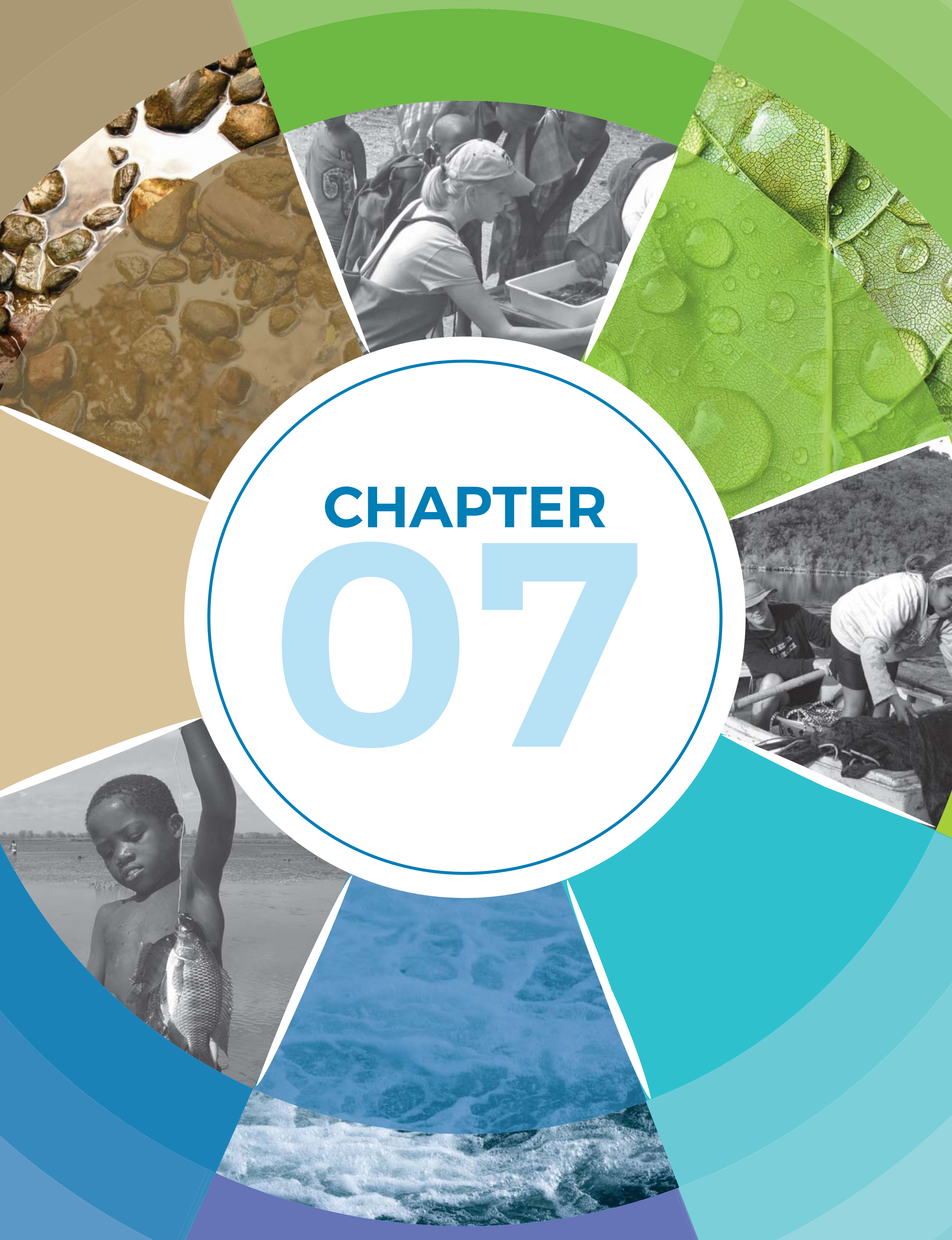
Conclusion

Both the implementation challenges and the emerging possibilities discussed in the preceding sections offer insights into the direction of future programmes of work by WRC relevant to water law. The experience with the incorporation of environmental water requirements into the National Water Act is pertinent here. It shows that programmes of work across a range of disciplines, not necessarily focusing on water law ***per se,*** are important to provide the necessary scientific underpinnings for the codification into law of the subjects of the research. The experience of the WRC presented in this chapter suggests that such a focus is necessary, as well as a more direct focus on law itself by legal researchers. Any coherent future research agenda for water law needs to take both into account. Horizon-scanning is crucial here, as the lag times for the initiation and completion of the lengthy, detailed research that is required to provide the foundations for any future revisions of our body of water law cannot be left until the opening of the window of opportunity created by an amendment process.

It will be important to guard against the temptation to rewrite the law in an attempt to solve problems arising not from inherent flaws in the law, but from shortcomings in how it is implemented. Recognising the difference, and accepting that elements of both are likely to be present simultaneously, will be key to designing and implementing appropriate interventions to enable a more rapid realisation of the vision and intent underpinning the Constitution and our body of water law.

In this respect, the WRC must continue, in the tradition established at the dawn of democracy, to play a role as a provider of relevant, credible knowledge to support ongoing law reform. Accompanying this is the need to support, and where necessary convene, communities of practice relevant to water law that can respond to issues with agility, legitimacy and the necessary degree of interdisciplinary and transdisciplinary collaboration. There is much to learn from the past, both the experience of post-1994 law reform and the implementation of its products, that can guide the future. This reflection and ongoing learning are a critical accompaniment to continuing to respond to emerging, immediate knowledge needs, while keeping an eye on the horizon.

CHAPTER 07



THE EVOLUTION OF ECOSYSTEM RESEARCH – FROM BIODIVERSITY TO BIOSSESSMENTS

James Machingura, Julie Coetzee, Belinda Day, Jenny Day, Duncan Hay, Paul Skelton, Christa Thirion and Mandy Uys

INTRODUCTION

When the Water Research Commission (WRC) was founded in 1971, water research throughout the world essentially encompassed hydrology, geohydrology and water quality, together with the practical application of these fields in agriculture and water supply. It was only in the 1980s that awareness gradually arose that the ecosystems supported by water that humans use might also warrant study. South Africa was one of the first countries to address the issue of what was then called "water for nature" (see, for instance, King and Pienaar 2011*), leading to the WRC funding research on aquatic ecosystems from the early 1990s.

It is worth quoting in some detail the very first mention of funding for "ecosystem" research. The following is taken from the WRC's 1989 Annual Report (pp 59-60).

"This research programme has its origin in the fact that water resources of some of the perennial rivers draining eastwards through the Kruger National Park (KNP) into Mozambique are barely adequate to meet existing demands. Of concern at present is the issue of allocating water in a rational manner to the numerous economic user sectors within these catchments. The KNP, one of the world's foremost conservation areas and an important contributor to the country's tourist industry, is recognised as one of these user sectors to which water must be allocated. However, water resource managers have recognised that South African knowledge and expertise in assessing minimum flow requirements of river systems is at present far too limited for concrete decisions to be made on water allocations to the KNP rivers as demands for water increase.

In March 1987 the Department of Water Affairs convened a workshop at which the water requirements of the KNP were discussed. The workshop concluded that relationships between water availability and ecosystem quality and functioning were almost completely lacking. It was therefore motivated that a co-operative multidisciplinary research programme should be initiated urgently. A small group of specialists subsequently met to compile a document which would incorporate the philosophy, goals and objectives of such a programme. This document was submitted to the executives of certain Government and statutory agencies (the WRC, Department of Water Affairs, Department of Environment Affairs, National Parks Board and the CSIR) who unanimously supported the concept of initiating a full-scale research programme to assess the water requirements of the KNP.

The aim of the programme is to develop the means to predict the impact on KNP river systems of changing flow regimes and water quality as the basis of a protocol for managing the allocation of water for ecological purposes. The objectives of the programme are to:

- *define and evaluate scientific information pertinent to the allocation of water to the KNP;*
- *develop the appropriate expertise for managing water allocation for ecological purposes;*
- *develop and maintain the necessary inter-institutional co-operation and communication;*
- *define and initiate research in priority areas …"*

The emphasis on the KNP reflects understanding current in the 1980s, that water should be allocated for maintenance of aquatic ecosystems of value for tourism (the KNP), as well as estuaries such as St Lucia in KwaZulu-Natal and the Palmiet in the Western Cape. It is fitting that the very first WRC-funded project to be completed under the aegis of Conservation of Ecosystems was 'The water rights of nature conservation', Project No. 350, by Adv M Uys (1991*). A description of the KNP Rivers Research Project was published by O'Keeffe and Y Coetzee in 1991* and the Final Report by Breen et al. in 2000*.

Since those early days, the WRC has become the major funder of research on rivers, wetlands and estuaries in South Africa. It should be pointed out, however, that virtually without exception, WRC-funded research on ecosystems has been of an applied nature, designed to feed into ecosystem management. South Africa still does not have dedicated research funding for deepening our understanding of aquatic (or terrestrial) ecosystem structure and functioning.

The ecosystem section of this book has three key themes – rivers, wetlands and estuaries. The topics cutting across all three ecosystem types are covered in the current chapter to avoid repetition. The current chapter starts by describing the WRC's contribution to our understanding of aquatic biodiversity (Jenny Day) and conservation (Belinda Day), followed by a discussion of the important work on South African fishes (Paul Skelton). We then deal with the practical issues of ecosystem management in the form of biological control of alien vegetation (Julie Coetzee), bioassessment of ecosystem condition or 'health' (Mandy Uys and Helen Dallas), and ecosystem services ending the chapter with a brief discussion of ecosystem services (Duncan Hay) and the contribution of the WRC to ecosystem management (Christa Thirion). Chapter 8 deals with rivers, chapter 9 with wetlands, and chapter 10 with estuaries.

BIODIVERSITY

'Biodiversity' is commonly defined as the diversity or variety of living things and can be viewed at the species, genetic and ecosystem level. The concept of biodiversity is relatively new, being popularised by the famous biologist EO Wilson in his book, ***Biodiversity***, in 1988. Monitoring biodiversity in South Africa is the mandate of the South African National Biodiversity Institute (SANBI), so biodiversity per se has not been the topic of most of the WRC reports discussed below. Nonetheless, the research reflected in them has been invaluable in improving our understanding of biodiversity, including genetic and ecosystem variability, as well as species richness, in South Africa.

Diversity of species

At least some reports are available on aspects of biodiversity across most taxa. These range from microbes such as bacteria, blue-greens, and algae, including diatoms, to invertebrates, frogs and fishes, and plants. Some of the reports include species lists, while others have identified organisms such as invertebrates to family level only. Nonetheless, the data in these reports represent very valuable information, sometimes from ecosystems that have since become degraded or entirely lost. The national Freshwater Biodiversity Information System (FBIS), developed by the Freshwater Research Centre (FRC) in Cape Town, now incorporates some legacy datasets of species (and water quality) generated by Dallas et al (1998*) and all the fish data from WRC reports that FRC personnel were able to source. Other than that, data only from the Western Cape has been captured. Until further funding becomes available, other WRC-generated species data will remain undigitised.

While most projects on algae and blue-greens have been done from a functional point of view (e.g. Harding and Paxton 2001*), a couple (Bate et al. 2004*; Ewart-Smith and King 2012*) also provide lists of species. Many ecological projects on rivers and wetlands have assessed invertebrate assemblages (see chapters 8 and 9), sometimes (e.g. Dallas 2002*, Schael and King 2005) providing checklists of species. Very little WRC-funded work has been done on frogs, the exceptions being Channing (1998*) and Vlok et al. (2012*), while studies on fishes have been extensive.

Ecosystem diversity

In an aquatic context, ecosystem diversity refers to the variety in space and time of rivers, wetlands and estuaries. The development of GIS tools has greatly assisted in digitising otherwise scattered maps and has proved very useful for collating information on ecosystem diversity. The reports by Van Riet et al. (1994a, b*) are some of the earliest to demonstrate the value of GIS in biodiversity studies.

Understanding South African aquatic ecosystems has been considerably expanded in the last twenty years or so, mostly by concerted efforts by the South African National Biodiversity Institute (SANBI) in conjunction with the WRC. Several projects (e.g. Ewart-Smith et al. 2006*) have been involved in the development of a South African wetland classification system, which parallels the wetland map covers produced by SANBI (e.g. Mbona et al. 2018*). A further invaluable project involving both the WRC and SANBI (Driver et al. 2011*) was the identification and mapping of Freshwater Ecosystem Priority Areas, this project being the first to identify areas of particular conservation importance, particularly for wetlands.

More specific projects have provided useful information on thermal springs (Olivier and Jonker 2013*), depressional wetlands ('pans' – De Klerk et al. 2016*), Ramsar sites (Malherbe et al. 2017*), estuaries (Whitfield 1995*), Western Cape rivers (Dallas 2002, Schael and King 2005*); Kruger Park rivers (Weeks et al. 1996*; Vlok et al. 2012*), and wetlands (Sieben et al. 2014*). The reader is directed to the relevant chapters for further information on rivers, wetlands and estuaries.

Figure 1. The research team who studied thermal springs in South Africa as part of a WRC project, namely Peter Nyabeze, Prof Jana Olivier, Dr Isaac Rampedi, Dr Ernest Tshibalo, Jaco Venter, Tshepo Motlakeng and Nelia Jonker. (Credit: Water Wheel archives)

Genetic diversity

Genetic diversity can be defined as variation in genetic information among individuals in populations and species. In some parts of the world, as in the south-western Cape of South Africa, even very similar-looking individuals of populations of fishes and many invertebrate groups are genetically (but not visibly) distinct from each other. For purposes of conservation, it is important to know the degree to which populations represent unique lineages, because each lineage, if lost, is irreplaceable. Although a number of WRC-funded projects has addressed the issue of genetic diversity in fishes, it seems that only one (Wishart et al. 2002*) has also examined invertebrates. This was one of the earliest genetic studies in the country to demonstrate the remarkable degree of genetic diversity in net-winged midges, stonefly nymphs and galaxiad fishes in the south-western Cape. Although very little further work of this kind has been funded by the WRC, those early reports identified the south-western Cape as being a centre of great genetic diversity, and led the way to numerous studies confirming the area as a biodiversity hotspot for invertebrates and fishes, as well as terrestrial plants.

More recently Matcher et al. (2014*) have entered the world of microbial diversity by addressing the issue of 'next-generation' sequencing. The idea is that, in the case of bacteria, it is possible to identify individual 'phylotypes' by sequencing the rRNA in water or sediment samples. No attempt is made to identify microbes to 'species' (a contested taxon in microbial diversity anyway) but to estimate the number of different types (phylotypes) in a sample. There is no doubt that this sort of technique will become common and valuable in the future, not only for bacteria but probably also for the assessment of aquatic plant and animal diversity. In this regard, the WRC very recently began to fund work on 'eDNA' (environmental DNS), as it is called.

Identification guides

Assessing the biodiversity of any group of organisms obviously requires accurate identification, to species level where possible. Texts on identification of aquatic organisms have traditionally been lacking for Sub-Saharan Africa. As a result, generations of students had to use guides to the aquatic invertebrates of North America and Europe, even though the taxa are often very different from the local ones. Recognising this gap, the WRC funded the production of a number of identification guides and the situation today is vastly improved. The following identification guides are currently available.

Diatoms	Taylor et al 2007*
Filamentous algae	Joska and Bolton 1994*
Wetland plants	van Ginkel et al. 2010*
Crustacea	Day et al 1999*; Day et al. 2001a*,b*
Lower invertebrates	Day and de Moor 2002a*
Molluscs and arachnids	Day and de Moor 2002b*
Diptera	Day et al. 2003*
Coleoptera	Stals and de Moor 2003*
Other insects	de Moor et al. 2003a*, 2003b*

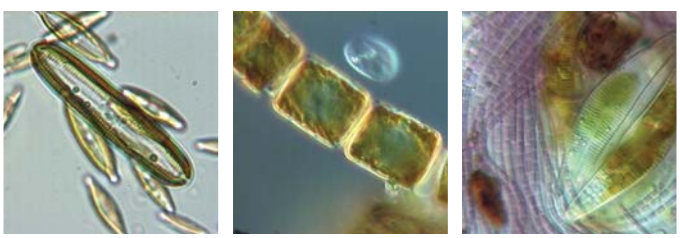


Figure 2. The WRC published a number of reports related to diatoms between 2004 and 2007. (Credit: Water Wheel archives)

As collecting effort increases, and new species are identified an d described, these guides become outdated. It is to be hoped that the WRC will encourage young systematists to contribute to biodiversity science by updating these volumes or contributing new ones to this valuable resource.

ECOSYSTEM CONSERVATION

INTRODUCTION

Freshwater ecosystems in South Africa are both degraded and very poorly conserved. The 2018 National Biodiversity Assessment (Skowno et al. 2019) found that only 33% of river length, 11% of estuarine area and 15% of inland wetland area, are in natural or near-natural condition, the remainder all being degraded to a greater or lesser extent. Indeed, 99% of estuarine area, 88% of wetland area and 67% of river length are critically endangered, endangered or vulnerable. Our water supply areas are similarly threatened. Only 18% fell within formal reserves in the 2011 NBA (Nel et al. 2011a*) and this figure had fallen to 13% by 2018 (Skowno et al. 2019).

This is the situation despite the South African National Water Policy (DWAF 1997), the National Water Act 36 of 1998 (RSA 1998a) and the National Environmental Management Act (RSA 1998b), which are considered to include some of the most progressive national water and environmental laws in the world, and which state the need to conserve and protect aquatic ecosystems and their biological diversity, "in order to secure ecologically sustainable development and use" of water resources (RSA 1998).

With this background it becomes obvious that research leading to the effective and sustained conservation of freshwater ecosystems and their biodiversity in South Africa has been, and continues to be essential, as does the implementation of the results of existing research.

WRC-funded conservation projects

The first mention of conservation by the WRC was in the 1974 National Master Research Plan and National Priority Research Programme (WRC 1974). The "conservation and management of catchments" was among its themes, although no research was done on the conservation of freshwater ecosystems until the Kruger National Park Rivers Research Programme (KNPRRP) began in the late 1980s. (more details provided further on in this chapter). This programme was the start of a long-term relationship between the WRC and South African National Parks (SANParks) that endures to the present.

Following the KNPRRP, there was no research in the 'formal' conservation sector (i.e. conservation biology and planning, the conservation of biodiversity and ecosystems, conservation within formal parks and reserves, and the conservation of individual groups or species) until 2002. In that year the WRC introduced Key Strategic Area (KSA) 2, which included a focus on ecosystem protection. Although a few projects have been funded in this sector. some of these funded projects provided seminal research.

One such study resulted in the reconnection of Lake St Lucia with the Mfolozi River after more than 60 years (Bate et al. 2011*). At the beginning of the twenty-first century, Lake St Lucia dried up and lost more than 90% of its total water area. This was due primarily to a lack of inflow because the estuary had been separated from the Mfolozi River in the 1950s, resulting in major changes to the functioning of the Lake St Lucia ecosystem. At the request of Ezemvelo KZN Wildlife, the WRC funded the Mfolozi/Msunduzi Indaba – a workshop during which information about the estuarine portions of the Mfolozi and Msunduzi rivers was collated and a management plan developed with the ultimate aim of re-linking the Mfolozi and St Lucia systems (Bate et al. 2011*). In 2012, the systems were linked via an old back-channel and thus had an indirect joint connection to the sea. A second workshop (the 2014 St Lucia Natural Science Symposium) was funded by the WRC to provide directions for research during after the recovery phase of the lake. All aspects of the lake's ecosystem and its future management, conservation and use were covered (Whitfield 2014*.

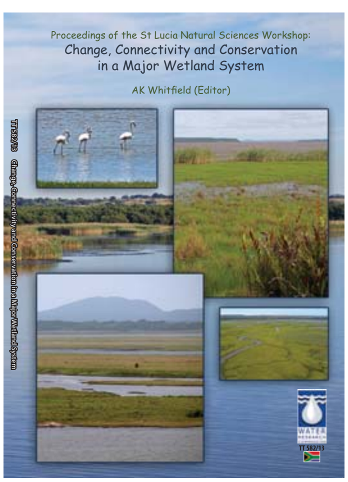


Figure 3. The report published following the 2014 St Lucia Natural Science Symposium.

Conservation of individual taxa or species

The WRC has largely been responsible for the conservation of freshwater fish in South Africa, but there has been little funding of research into the conservation of any other individual taxa. The only other species that has been studied extensively (at the bequest of the Kruger National Park Scientific Services), is the Nile Crocodile in north-eastern KwaZulu-Natal (Downs et al. 2015*). Crocodiles are considered a sentinel species (a top predator, and indicator of ecosystem and food web integrity or health) and recent Nile Crocodile deaths in South Africa prompted an investigation into their conservation status (including their health, biology, reproductive ecology and population status), and resulted in recommendations regarding their conservation and management (Downs et al. 2015*).

Figure 4. Crocodile mortalities in the Kruger National Park's Olifants Gorge and Lower Letaba River in 2008 due to pansteatitis led to the establishment of a multi-institutional collaborative research programme, known as the Consortium for the Restoration of the Olifants Catchment (CROC). (Credit: Water Wheel archives/SANPARKS)

Systematic conservation planning

Systematic conservation (biodiversity) planning (Margules and Pressey 2000) provides a structured process for the identification of biologically significant priority areas for conservation and is a discipline in which South Africa is considered a world leader in the terrestrial field (Balmford 2003). In 2003, the CSIR and DWAF announced the development of a national policy and planning framework for the conservation of inland water biodiversity in South Africa, using systematic conservation planning. The WRC funded a pilot project in the Fish-to-Tsitsikamma Water Management Area (Nel et al. 2006*), in which the policy and planning tools were tested and refined. Stakeholders were included in the development of a planning method for the prioritisation and selection of the freshwater ecosystems to be conserved.

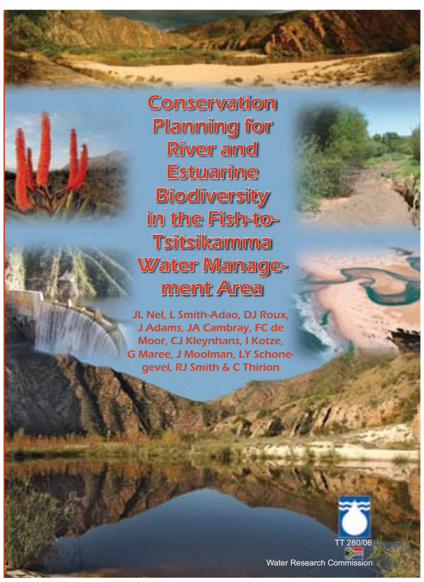


Figure 5. The final report of the WRC-funded pilot project in the Fish-to-Tsitsikamma Water Management Area in which the policy and planning tools were tested and refined.

Systematic conservation planning requires the setting of targets (how much of each biodiversity feature needs to be protected) within the planning process. These targets are usually based on expert opinion but a new method, based on established measures of species diversity, was developed for determining conservation targets for river lengths (Rivers-Moore 2011*). The current conservation target in South African freshwater planning is 20% of each major inland water ecosystem type (Roux et al. 2006*), although a blanket approach is inadequate because it assumes uniform species distribution within, and between, rivers. Recently, systematic conservation planning has been used in the National Freshwater Ecosystem Priority Areas (NFEPA) project (Nel et al. 2011a*, a multi-funded project, co-funded by the WRC. The project identified strategic spatial priority areas that would, if conserved, meet the national goals of water resource protection as required by the NWA and NEMBA as well as expanding the network of protected areas (as required by the NEMPA), thus supporting the sustainable use of water resources. Biodiversity targets were recommended by specialists and input from more than 100 aquatic scientists, managers and practitioners was incorporated into the development of National Freshwater Ecosystem Priority Areas (NFEPAs) in an extensive stakeholder engagement process. A series of FEPA maps (Nel et al. 2011b*) was developed and guidelines were provided to allow the effective use and application of NFEPAs within the bounds of South African policy and legislation (Nel et al 2011a*). An institutional basis for their effective uptake and protection was also developed and guidelines were provided for decision-makers as to appropriate activities within NFEPA areas (Driver et al. 2011*).

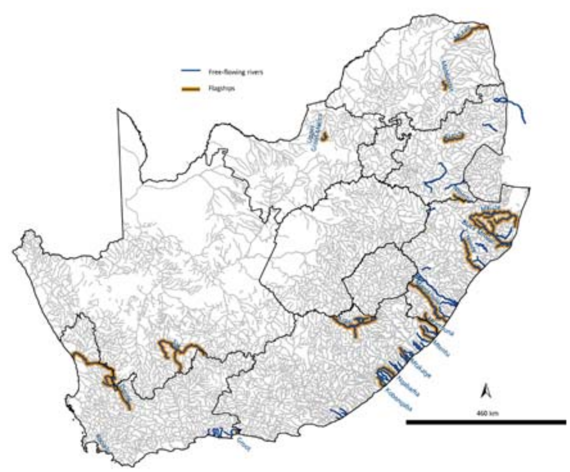


Figure 6. South Africa's last's free-flowing rivers, as identified in the Atlas of Freshwater Ecosystem Priority Areas in South Africa. (Credit: Nel et al, 2011a)

NFEPA products provide a hierarchy of conservation priorities for all South African aquatic ecosystems, and were intended to give guidance, and provide credence for the conservation of freshwater ecosystems to decision-makers in all national and provincial departments, catchment management agencies, stakeholders, national and provincial conservation agencies, SANBI, municipalities, NGOs, conservancies and environmental consultants (both for EIAs and Reserve determination). The NFEPA maps have proved to be a very successful tool for the protection and conservation of South African freshwater ecosystems. They have been used in Ecological Reserve determination, water resource classification and the issuing of water licences as well as integrated water resource management plans in water management areas. Conservation agencies use the maps for planning. For example, CapeNature has prioritised the stocking of alien fish, and clearing of invasive alien vegetation, according to NFEPA maps. In addition, the 19 free-flowing NFEPA 'flagship rivers' have remained intact since being identified and prioritised in 2011 (Skowno et al. 2019).

Data banks

The WRC has also funded the establishment of national databases that may be used for, inter alia, conservation planning. These include the National Wetland Vegetation Database (Sieben et al. 2014*) in which one of the aims was classification of wetland vegetation types in order that targets could be set for wetland rehabilitation and strategic conservation planning. Wetland vegetation types were classified, indicator species were identified where possible, and detailed community composition was linked to environmental variables, which were then proposed as drivers of community composition. Species response-curves were also constructed, in some cases for groups of species that occurred together.

Policy and governance issues

The policy, legislation, planning, management and enforcement of South African water resource and biodiversity management are complex, as are their protection and conservation. This is due to legislation and decision-making being shared by multiple sectors and spheres of national, provincial and municipal government. This often results in confusion and 'passing the buck' within departments, and ultimately in the failure to implement conservation recommendations and initiatives. Roux et al. (2006*) therefore investigated the development of shared (inter-departmental) policy objectives and guiding principles for conserving South Africa's inland water biodiversity. A formal cross-sector policy statement and cooperative implementation plan for the conservation of inland water biodiversity in South Africa was formulated. In order for these national objectives to be achieved, multiple agencies, each with their own roles and responsibilities, need to cooperate and work together effectively. Roux et al. (2009*) then investigated the effective implementation of these national goals and cross-sector policy objectives for conserving freshwater ecosystems by operational agencies at sub-national levels (Roux et al 2009*). A method, founded within the principles of adaptive management, was developed for facilitating cooperative and sustained conservation action amongst these agencies, and implementation guidelines for the measurement of their success and effectiveness were formulated.

Socio-cultural aspects of conservation

The socio-cultural aspects of conservation planning have also been addressed. Relationships between the presiding socio-economic and political landscape, and freshwater conservation planning and implementation, were studied, as were ways of incorporating political and socio-economic issues (including an understanding of river ethnology) into the freshwater conservation planning process (Patrick et al. 2008*). These authors suggest that a national research strategy should be implemented and ecosystems redefined as "social-ecological" systems to encourage this process. They furthermore suggest that the effectiveness and success of freshwater conservation initiatives may be improved by encouraging societal "buy-in" if socio-economic and political aspects are included in the conservation planning process. Transdisciplinary and trans-mandate coordination and co-operation, transparency and the implementation of an adaptive learning process were also recommended.

The socio-cultural perceptions regarding freshwater conservation (i.e. the extent to which people understand and care about conservation, and how that influences their actions) were examined, and a test study done in the Greater Kruger area (Nortje et al. 2011*). Actor cluster groups (people with different degrees of "knowing, acting and caring") were identified, and an attempt was made to identify how the conservation planning process and catchment management strategies could address the barriers to changing mental models in order to increase the success of conservation initiatives. The authors concluded that solutions cannot come from within the natural sciences or from within the conservation process itself but rather from the social sciences.

'Informal' conservation-oriented research

Although the above-mentioned research has been done in the 'formal' conservation sector, the vast majority of the research funded by the WRC has focused on development- and management-oriented protection (and by implication, conservation) provided by inter alia the National Water Act and NEMA. Probably the greatest contributions by the WRC to the conservation and protection of freshwater ecosystems in South Africa have been indirect. In fact, all WRC-funded research that has resulted in an improved understanding of ecosystem functioning, ecology and biodiversity of freshwater ecosystems; better-informed and more rigorous recommendations to politicians, decision-makers, planners and managers; and the effective conservation, management and monitoring of freshwater ecosystems, may be considered part of informal conservation-oriented research. For the purposes of this section, however, only the projects that are specifically conservation-oriented have been included. Details of other projects are discussed in the relevant chapters.

Conclusions and recommendations

Much WRC-funded research on the management of freshwater ecosystems has resulted in indirect benefits for the protection and conservation of these systems. Formal research into conservation issues has, however, received far less funding although that which has been done has resulted in some significant achievements. For example, the IFR methods; processes emanating from the KNPRRP; FEPA maps; relinking the Lake St Lucia ecosystem with the Mfolozi River; and the conservation of South African freshwater fishes, have been almost entirely due to funding from the WRC.

It is, however, alarming to note that the environmental integrity (condition) of South African aquatic ecosystems, as well as their levels of protection and conservation, have decreased from 2011 to 2018 (Skowno et al. 2019). For example, 14 of the 62 free-flowing rivers identified in the NFEPA project lost their status due to the decline in their condition. Ten of these rivers lost 100% of the areas classified as 'natural' and 4 lost more than 50% (Skowno et al. 2019). Obviously then, interventions such as environmental impact assessments (EIAs), IFRs (including freshwater flow allocations), rehabilitation, NFEPAs, and improved governance structures and planning and management guidelines have only partially achieved their goals. Increased attention to the effective conservation of aquatic ecosystems and their biodiversity is therefore vital.

Whilst the obvious and pressing need exists for continued research (and funding) into the use and management of aquatic ecosystems for human use, it should not be forgotten that the protection and conservation of these same systems is fundamental to their continued functioning (and is enshrined in the NWA, amongst others). Just as critical is the funding of fundamental research that underpins conservation planning and management frameworks.

50 YEARS OF RESEARCH ON FISHES

INTRODUCTION

Fish are for the most part indirect elements in WRC reports. There are a few focused studies that deal with one or other aspect of particular species, often bio-ecological studies on iconic or threatened taxa. More frequently, though, projects involve fish communities in studies for river conservation, including Instream Flow Requirements and fish ladders for management purposes and aquatic conservation planning;

management of alien fish; pollution and toxicology; ecosystem monitoring, and development of artisanal fisheries. Manuals providing methods for using fishes in these studies also feature. The studies tend to be clustered in areas in the country where key researchers reside or where a particular project is located, as for instance in the KNP. Estuarine fish studies are not considered here.

Fish genetics and systematics

Although systematic studies are not generally the subject of WRC projects, a few studies considering population genetics have yielded useful systematic insight into species. Motivated by a concern that the 1998 Water Act empowers the Minister to transfer water between river basins with the potential of mixing of gene pools of organisms, for instance, Wishart et al. (2003*) studied the genetics of populations of ***Galaxias*** from streams in and around the Cape Peninsula. This study indicated a higher degree of genetic characterisation of ***Galaxias*** populations, than recognised at that time, suggest greater species diversity. than indicated morphologically. Subsequent research over the range of the genus in South Africa has confirmed that the species composition is completely underestimated taxonomically.

Another instance where WRC-supported systematic research was a project on suckermouth catfish of the genus ***Chiloglanis***, which are small rheophilic species with a characteristic sucker mouth used for adhering to the surface of rocks in flowing water. They have potential for assessing minimum flow requirements of riverine taxa (Matlala et al. 2010*). The project aimed at resolving the distribution and variation of these species in the Limpopo system in order to formulate suitable river management recommendations. Both morphological and molecular methods were used in the study. Data relevant to systematics of species has been generated by other projects, for instance for ***Labeobarbus polylepis*** (O'Brien 2011*) and ***Opsaridium peringueyi*** (Venter et al. 2010*).

Conservation biology and ecology of fish

The conservation of threatened fish species in South Africa has received both direct and indirect attention by WRC-funded research. Pollard et al. (1996*) reported on the impact of drought on the macro-invertebrate and fish populations of the Sabie-Sand River as part of a pre-impoundment study. The study presents a unique data set on the fishes of this lowveld river that records the changing population dynamics in the drying river and its pools as a drought progressed, providing extraordinary insight for management and conservation as to the habitat preferences and resilience of different species.

Venter et al. (2010*) provide a guide for the development of conservation plans for threatened fish species in South Africa. The study focused on the threatened endemic rheophilic cyprinid ***Opsaridium peringueyi*** as a test species that allowed for the development of general methods for species-level Biodiversity Management Plans (BMP-S). The conservation biology of threatened freshwater fishes in the Olifants River (Western Cape), was another fish-focused programme linking to conservation also of the river itself (Bills and Impson 2013*). This programme included studies on a number of somewhat obscure smaller endemic stream fishes, the rock catlets ***Austroglanis barnardi*** and ***Austroglanis gilli***, and the Twee River redfin ***Sedercypris erubescens***, that are easily overlooked when attention is directed to larger iconic species. Training and education were included in that study, which embraced biological, maintenance and culture, and genetics, as well as ecology, in the development of BMP-S for the target species.

Smit et al. (2013*) studied the conservation of tigerfish (***Hydrocynus vittatus***) in the KNP in order to establish water quality and quantity requirements for this iconic flagship species. Fish health and bio-accumulation of pollutants were part of the study linking it with a number of other fish studies focused more directly on those aspects (see below). As a highly mobile top predator in the systems, the study concluded that tigerfish were good indicators of water quantity but less so for water quality.

Fish are considered valuable components of both Alpha and Beta diversity in setting systematic conservation targets for rivers (Rivers-Moore 2011*). Existing fish distribution data allowed for the comparison of fish as measures of longitudinal diversity in three relatively free-flowing rivers in KwaZulu-Natal, the Mkuze, the Mvoti and the Mzimkulu, where fish were significant at the level of Alpha but not at Beta diversity. The Cape Critical Rivers Project managed by the Freshwater Research Center (Matthews 2013*) focused on the biological needs of highly threatened fishes in order to identify the critical threats and areas that require attention to river conservation. The project produced several key reports (Paxton 2008, Paxton et al. 2012) that advanced our knowledge of the Clanwilliam sandfish (***Labeo seeberi***) the Clanwilliam yellowfish (***Labeobarbus seeberi***) and Clanwilliam sawfin (***Cheilobarbus serra***) all highly threatened and iconic species in the Clanwilliam Olifants River system.

Figure 7. The WRC has funded several studied on yellowfish species, including the smallmouth yellowfish. (Credit: WRC archives)

Yellowfish – a general term for large riverine cyprinids in southern African rivers – have assumed a high profile, iconic status in terms of riverine conservation. This is in part due to being strongly promoted by an active citizen action group, The Yellowfish Working Group (YWP), which is sponsored by the Federation of Southern African Flyfishers (West 2014). Wolhuter and Impson (2007*) produced an excellent overview of the state of yellowfishes in South Africa under the auspices of the YWG, with chapters contributed by a wide range of researchers, academics and anglers. A second compendium, focussed on the yellowfish of the Orange-Vaal river system, was compiled by O'Brian and De Villiers (2011). In this account the biology and ecology of two valuable angling species, ***Labeobarbus kimberleyensis*** and ***L. aeneus***, were dealt with in detail, including movement studies by means of telemetry. A guide to telemetry techniques developed through these studies was provided by O'Brian et al. (2013). Case studies during the development of the techniques involved the Lowveld largescale yellowfish (***Labeobarbus marequensis***) and the tigerfish (***H. vittatus***) within the Crocodile (Incomati) river. Another study, in Boskop dam and the Vaal-Orange, involved the smallmouth yellowfish (***L. aeneus***) and monitored movement in relation to diurnal, lunar and seasonal cycles. The studies showed that the telemetric systems developed in South Africa were superior to those from elsewhere.

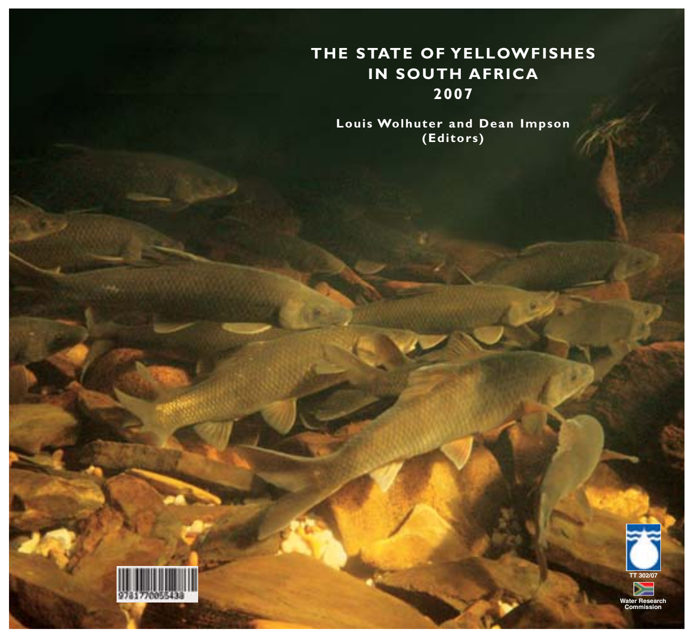


Figure 8. The report on the state of yellowfishes published by the WRC in 2007.

A number of other fish tracking studies have been conducted through WRC-funded programmes. The earliest was work carried out by Paxton (2004*) on large cyprinids in the western Cape Olifants River system. Dams and water extraction in this system are implicated in the decline of the several large endemic cyprinids, for which migration was suspected but unknown in detail prior to these investigations. Later, two large cyprinids were studied, the Clanwilliam yellowfish (***Labeobarbus seeberi***) and the Clanwilliam sawfish (***Cheilobarbus serra***), our knowledge of ***C. serra*** being considerably advanced and linked to the critical flow requirements of the species throughout their life cycles (Paxton and King 2009*). This allowed for clear recommendations to be made for the necessary conservation and community-level interventions needed for these species.

Another yellowfish study (O'Brien and de Villiers 2011*) focused on the Bushveld small-scale yellowfish ***Labeobarbus polylepis***. The biology and ecology of several populations of the species were examined and extended to genetics, morphology, and metal concentrations derived from feeding habits. Significant genetic differences between the samples studied indicate that the taxonomy of the lineage is yet to be settled, which has clear conservation implications. Yellowfish are valued indigenous angling targets in South African rivers and dams (Brand et al 2009*). In response to conservation and ethical concerns recreational angling frequently encourages the return of live fishes caught to the water body. The physiological response of smallmouth yellowfish (***L. aeneus***) to angling was a specific WRC project that addressed issues raised by this practice (Smit et al. 2011*). The guidelines provided by the report were designed to reduce stress and mortality during the catching and landing of fishes as well as suggestions on the management of angling such as bag limits and closed seasons.

River ecology and fish

A pre-impoundment study on the distribution of fishes of the Sabie-Sand River (O'Keefe and Coetzee 1996*) provided valuable data on fishes for the initial phase of the Kruger National Parks Rivers Research Programme (1988-1992). The physical habitat requirements of selected species were here reported for the first time. The report highlighted the lack of, and need for, further detailed breeding information of the species as these specific data are needed for the conservation and management of the KNP rivers. Available data, as obtained from published literature, were recorded later by Muller and Villet (2004*), who concluded that the fish communities of the major KNP rivers were similar overall.

Fish were one of the taxa contributing to the biotic integrity of the Luvuvhu and Mutale rivers, as reported by Fouche et al. (2001*, 2005*). The study provides details of the species and their habitat preferences in the two rivers, and included trophic niche determination of each species. It was found that fish responded more noticeably to water quality variables than did macroinvertebrates and are therefore more suitable bio-indicator organisms. Two fish-derived indices of habitat integrity were compared in the process of selecting the study sites and, although both indices agreed on site integrity, the rapid method proposed by Gaigher and Fouche (2001*) also allowed for an indication of change in abundance.

Figure 9. Labeobarbus kimberleyensis. (Credit: Paul H Skelton)

Fishways

The longitudinal and dynamic flow nature of river flow, coupled with fishes as mobile creatures that frequently migrate both upstream and downstream, determines that the provision of fishways over man-made obstructions is often a necessary conservation intervention. A specific Fishways Research Programme was funded by the WRC and produced a series of valuable reports that provided essential data on fish and fishways in South Africa and, critically, the guidelines for the planning, design and operation of fishways in South African conditions (Heath et al. 2005*, Bok et al. 2007*). The programme determined that there were 57 fishways in South Africa, of which 42 were then at least partially functional, as well as identifying the species of fish that used such fishways. Other findings indicated that Southern African fishes can negotiate fishways with greater levels of velocity and turbulence than reported elsewhere, with implications for local fishway construction. One of the most visible outcomes of the fishway focus in South Africa is a semi-natural diversion of the Sabie River at the crossing close to Lower Sabie camp in the KNP where, under suitable conditions, the public is readily able to see a functional fishway in operation (Heath et al. 2005*).

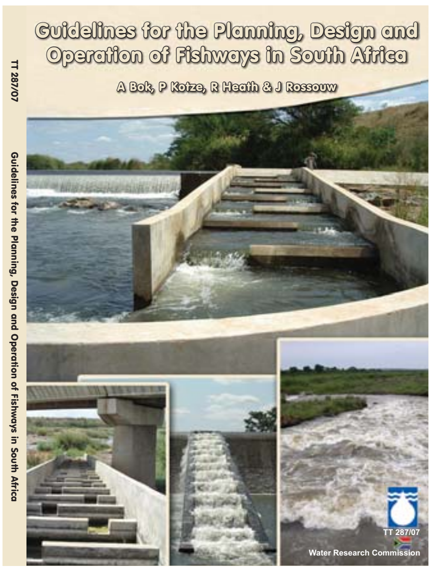


Figure 10. The Fishway Research Programme resulted in a comprehensive guideline for the design and operation of fishways in South Africa.

Invasive fishes

The impact of invasive fish species on aquatic biodiversity is a global issue and a matter of considerable attention in South Africa, having consumed much energy and time in the development of the National Environmental Management Biodiversity Act (Act no. 10 of 2004) (NEMBA). The development of a decision-support framework for prioritising management actions for invasive fishes is an area of research supported by the WRC (Kimberg et al. 2014*). Several case studies were part of this investigation, one on the Sundays River, where fishes have invaded the system through various pathways including interbasin transfer canals (Kimberg et al. 2014*); a second studied the Groot Marico (Limpopo) catchment, where American black bass (*Micropterus salmoides*), a common alien fish predator introduced as an angling target, is the subject species (Kimberg et al. 2014). The impact of this invader was also studied in an Eastern Cape mountain stream (The Blindekloof, Swartkops river system, near Uitenhage) (Kimberg et al. 2014*). The impact of various bass on small riverine cyprinid species is of particular concern as bass are widespread aliens in southern Africa. The successful eradication of smallmouth bass from an invaded tributary (the Rondegat River) of the western Cape Olifants River has been showcased in a series of reports and other publications (Woodford et al. 2012*; Marr et al. 2012*, Impson et al. 2013, Jordaan and Weyl 2013, Weyl et al. 2013, Slabbert et al. 2014, Bellingan et al. 2015, Dalu et al. 2015, Weyl et al. 2016*). An associated study was done in the Krom River tributary of the Olifants system focused on capacity building (Marr et al. 2019*).

A surprising outcome of an investigation into large-scale crocodile deaths in the Olifants River within the KNP was that pansteatitis (hardening of fatty tissues) was the direct cause, but indirectly this was the result of the crocodiles feeding on sharptooth catfish (***Clarias gariepinus***) and, in particular, an invasive filter-feeding fish species, the silver carp (***Hypopthalmichthys molitrix***) (Huchzermeyer 2012*).

Figure 11. The monitoring team at work in the Rondegat River. Extensive surveys were undertaken both prior and after the treatment of the river with rotenone. (Credit: SAIAB/ Olaf Weyl)

Fish for food: toxicity, pesticides and human health

The northern Olifants river (tributary of the Limpopo), one of the major rivers transversing the KNP, has been described as the most polluted river in Africa. Its upper reaches drain the extensive coal-mining area of Highveld Mpumalanga; immediately adjacent to the western border of the KNP at Phalaborwa it is impounded in order to service a massive metal and mineral mine in the vicinity of the town of Phalaborwa. The river has suffered numerous spillages and sediment surges over many years, with resultant fish kills of major proportions. Van Vuuren et al. (1994*), in an early study on pollutants in the Olifants, focused their investigation in the Phalaborwa area on bioaccumulation of various pollutants, including copper, in the organs of various fish species More recently, Huchzermeyer (2012*: iv) has stated, "The results suggest that pollution derived nutrient enrichment of rivers can have far reaching effects where man-made hydrodynamic change has altered the aquatic habitat. Such information is important to guide conservation policy and decisions regarding use of water and safety of fish consumed from such waters."

Heath and Claasen (1999*) provided an overview of pesticide and metal levels present in populations of larger indigenous fish species of selected South African rivers. The report focused on the rivers of the KNP as well as the Berg River in the Western Cape. Fish species with the highest metal levels were ***Labeo rosae***, ***Oreochromis mossambicus***, ***Cyprinus carpio***, ***Clarias gariepinus***, ***Labeo ruddi*** and ***Labeo congoro***, all essentially sediment feeders. Pesticides were mostly concentrated in fatty tissues and the highest concentrations were found in mainly carnivorous fish. A resulting guide to freshwater fish and human health (Heath et al 2004*) provided a fish health assessment index (HAI) and a protocol for the assessing fish health. An applied study of contaminated fish from the Rietvlei Dam has also been reported by Barnhoorn et al. (2011*).

Rall et al. (2010*) suggested the development of a bioaccumulation monitoring programme and provided protocols for acute fish toxicity bioassays. The study included a number of indigenous species and concluded that, although there is no single species suitable for all applications, the minnow ***Enteromius trimaculatus*** was the most suitable species to use.

Fisheries and aquaculture

Figure 12. The WRC has supported various studies dealing with inland fisheries and development of aquaculture in rural communities. (Credit: WRC archives)

The WRC has supported various studies dealing with inland fisheries and development of aquaculture in rural communities. A comprehensive scoping study on the development and sustainable utilisation of inland fisheries in South Africa was conducted by Britz et al. (2015*). The review covered property rights, legislation, governance, indigenous knowledge, recreational fisheries, dam fisheries potentials, institutional and organisational structures, technology transfer and capacity building. Essentially the productivity of inlands water is too low to support large-scale fisheries and therefore small-scale and recreational fisheries are the only real options in South Africa. This will require a reform of policy, legislation and governance structures by the Department of Forestry and Fisheries (DAFF). The role of state hatcheries was reviewed and it was recommended that a wider multi-purpose role for such hatcheries be encouraged. A set of recommendations for the development of the industry that embraced a 'Value chain approach' was made.

In a more constrained study Harding and Koekemoer (2011*) reported on the fishery assemblages in a suite of dams in relation to the management of such waterbodies. The study was premised on the assumption that the fish populations in the dams are imbalanced by so-called 'coarse' fish species as common carp (***Cyprinus carpio***), sharptooth catfish (***Clarias gariepinus***) and canary kurper (***Chetia flaviventris***) that disturb the foodweb and favour eutrophication. Management by selective removal should restore a balance in favour of a more desirable foodfish, ***Oreochromis mossambicus***. Other aquaculture-related projects include the development of a training manual for trout cage-culture in irrigation dams (Salie et al. 2008*) and an investigation into the fisheries potential of Lake Nandoni (Fouche et al. 2013*).

The involvement of rural communities in aquaculture is the focus of a programme conducted by Rhodes University's Rural Fisheries Programme (Rouhani and Britz 2004*, 2011*). An initial baseline study (Rouhani and Britz 2004*) indicated that rural aquaculture was essentially non-existent in South Africa but had potential if the necessary support is provided for training, and suitable infrastructure, is available, including several existing state hatcheries that need to be rehabilitated. The final outcome of the programme found that both private and public participation was necessary to overcome existing constraints to the industry (Rouhani and Britz 2011*).

Fish and climate change

Climate change is one of the major threats to biodiversity and ecosystem functioning. Dallas et al. (2017*) made the first attempt to predict the potential impact of climate change on freshwater fishes in the Cape Fold Ecoregions (CFE), an area that is expected to experience higher water temperatures and decreased runoff over the next 50-100 years (Schulze 2011*). These predicted changes in river flows and instream water temperatures may increase the risk of extinction of vulnerable native fish communities in South Africa (Dallas & Rivers-Moore 2014). Dallas et al. (2017*) further assessed the influence of climate change on native and non-native freshwater fishes in the CFE, improving knowledge on the vulnerabilities of freshwater fish and threats to their continued existence. For instance, the research findings of Dallas and colleagues suggested that thermal tolerances and preferences vary significantly amongst species. This information is critically important for monitoring, management and conservation of fish and associated aquatic habitats.

A noteworthy database (Dallas et al 2021) houses all the existing records of fish distributions in the CFE. This database was used to develop the first species-distribution models for CFE freshwater fishes, hence allowing the first predictions as to how fish distributions are likely to be influenced by different climate-change scenarios.

General

Additional projects dealing to some extent with fishes include the following. A book on the ***Rivers and wetlands of Cape Town*** (Brown and Magoba 2009*) featured the occurrence of fish in rivers and estuaries. Fish were reported for each of the designated Ramsar wetlands in South Africa by Malherbe et al. (2017*). Data on threatened freshwater fish taxa in South Africa were used to designate certain rivers as 'fish sanctuaries' as well as 'fish migration areas' and 'fish upstream management areas' in the Atlas of Freshwater Ecosystem Priority Areas (Nel et al. 2011*). Kleynhans (2008*) developed a Fish Response Assessment Index (FRAI) for use in river eco-classification. The fish community of the Orange River mouth was used as a means of determining the environmental state of that ecosystem by Seaman and van As (1998*). Fish were considered as one of many factors in the assessment of the ecological and economical evaluation of wetlands by Palmer et al. (2002*) and of Nylsvlei by Vlok et al. (2006*). The application of triploid grass carp as biological control agent for aquatic weeds in irrigation canals was reported by du Plessis and Steyn (2003*).

Figure 13. Liesbeek River, which runs through Cape Town. (Credit: Petro Kotzé)

Conclusions

Over the years the WRC has clearly supported many projects that include the study of fish. The purpose of these studies has always been directed towards human interests in the environment, fish as indicator organisms of river health and management, as valuable or threatened ecological elements, or as economic targets relevant to human needs. The studies have contributed significantly to our knowledge of the biology and ecology of freshwater fishes in South Africa that otherwise would have remained unexplored. In this respect, WRC support for fish research over the past 50 years has probably exceeded that from any other sector including the national and provincial agencies responsible for nature and environmental conservation. This realisation is of more than casual relevance: it demonstrates the key role of the WRC in all things related to water, including river health and the conservation of aquatic life in natural systems in South Africa, most of which are impacted by human activities to an ever-greater extent.

INVASIVE ALIEN PLANTS AND THEIR CONTROL

INTRODUCTION

South Africa has a long history of investigating, regulating and managing biological invasions dating back over 100 years, and is one of the leading countries in terms of research on biological invasions (Pyšek et al. 2008). The country has a strong collaborative network of researchers (Abrahams et al. 2019), and has one of the most active communities globally, with strengths in theoretical and applied invasion science, and world-leading expertise in specific sub-disciplines (e.g. the classical biological control of invasive plants) (Van Wilgen et al. 2020). While most of the country's fundamental research into, and management of, invasive alien plants (IAPs) is funded by the Department of Forestry, Fisheries and Environment through their Natural Resources Management Programmes (initially Working for Water), the WRC has contributed to several programmes that have enhanced our understanding of the impacts of invasive alien plants (IAPs), leading to improved management.

A wide variety of tree species that were introduced to South Africa over the past few centuries to address timber shortages have become the worst invaders with the greatest impacts, arguably, on South Africa's fresh water economy, through reduction in mean annual runoff (MAR) (Richardson et al. 2003; Le Maitre and Görgens 2003*). The greatest estimated impact is due to wattles (***Acacia mearnsii, A. dealbata*** and ***A. decurrens***) which account for 34% of the reductions, followed by ***Pinus*** species (19.3%) and ***Eucalyptus*** species (15.8%) (Le Maitre et al. 2016). Recognising the impact of invasive plants on the South African economy, South Africa launched the Working for Water (WfW) programme in 1995, which had the dual purpose of protecting our vital water resources from reduction due to invasive plants, while simultaneously providing employment and developmental opportunities to disadvantaged people in rural areas. WfW has substantially broadened the scope and extent of alien species management projects in South Africa and has pioneered regulatory approaches to address invasions (Van Wilgen and Wannenburgh, 2016).

Soon after the establishment of WfW, in January 1996, the WRC appointed the CSIR to carry out a research project on behalf of the WfW Programme. The objectives of the project were to determine the extent of invasions by alien plants, their impact on surface water resources and the costs of controlling the invaders, and to devise a national strategy for a control programme (Versfeld et al., 1998*. The prediction from that study was that alien plant invasions would lead to substantial reductions in water runoff from catchment areas (Versveld et al. 1998*) and provided the economic motivation to initiate large-scale alien plant control operations (van Wilgen and Wannenburgh 2016). Indeed, Prof Kader Asmal, the then Minister of Water Affairs and Forestry, who initiated the WfW programme, wrote in his Foreword to the report that "This critically important report has given us, for the first time, a picture of the extent to which South Africa has been invaded by alien plants, and the enormity of the challenge facing the Working for Water programme". At the time, it was estimated that more water could be delivered, at a lower unit cost, by integrating alien plant control with the maintenance of water supply infrastructure, than without control (van Wilgen et al. 1996).

Riparian invaders

Currently, there are 759 terrestrial and 19 aquatic plant species declared invasive, under the South African National Environmental Management: Biodiversity Act (NEMBA 2014). Arguably, the suite of trees introduced from many other parts of the world to provide timber is now one of the biggest threats to South Africa's water resources, as the majority of these invasions are within riparian areas that have readily available water and are difficult to manage (Kotzé et al. 2010). The deep fertile soils with high soil moistures associated with riparian areas, make them ideal for plant establishment and growth (Everson et al. 2007*). While these trees were introduced to provide ecosystem services to support growing human populations in the absence of indigenous counterparts, they have become rampant invaders in catchments of most of South Africa's biomes, in particular the fynbos and high-elevation grassland regions of the country. In 1996, Versveld et al. (1998*) estimated that 10.1 million ha of South Africa and Lesotho were invaded by invasive trees and woody shrubs, an area larger than KwaZulu-Natal. The Western Cape was the most heavily invaded at about a third of the total area, followed by Mpumalanga, KwaZulu-Natal and Limpopo Provinces. These invasives increase above-ground biomass and evapotranspiration, resulting in decreased surface water runoff and groundwater recharge (Görgens and Van Wilgen, 2004). The reduction in surface water runoff (mean annual runoff: MAR) as a result of these invasions was estimated to be 3300 Mm^3 in 1996 (about 7% of the national total (Versveld et al. 1998*), most of which is from the fynbos and grassland biomes (Le Maitre et al. 2000). The most recent estimate of the national impacts of invasive alien plants on river flows, however, is that they reduce MAR by about 1.44 billion m^3/year, or 2.9% of the naturalised mean annual runoff, which is 50% of the previously estimated losses (Le Maitre et al. 2016).

Since 1995, WfW has spent R15 billion (unadjusted for inflation) on alien plant control operations across South Africa (Le Maitre et al. 2020). Following the findings and recommendations of Versveld et al. (1998*), as well as the opportunities for quantifiable data collection provided by WfW clearing operations, a number of WRC-funded studies have investigated various aspects of tree and shrub invasions on, for example, dam water yields (Le Maitre and Görgens 2003*); water use before and after clearing alien vegetation; and riparian ecosystem functioning, and restoration, following clearing. Chamier and Le Maitre (2001*) also investigated scenarios allowing for the development of techniques to estimate:

- monetary costs of achieving effective control of water using invasive plants in the different provinces in South Africa
- the amount of time taken to achieve significant reductions in water lost due to alien invasion resulting from varying rates of expenditure on control
- the impact that biological control could have on control costs in the long term

This scenario planning paved the way for future research into IAP costs, and management options.

In South Africa, there is a limited understanding of the extent to which tree species (particularly those in riparian areas) contribute to total evapotranspiration (ET). In order to quantify reductions in water availability as a result of invasions, Le Maitre and Görgens (2003*) investigated the impacts of invasions by alien plant species on the assurance of supply from typical dams in typical catchments. They concluded that it is feasible to estimate the potential streamflow reduction impacts by invasive species on utilisable water in South African river systems (expressed as yield from impoundments) for which reasonably reliable databases on invasion patterns exist, but that more data needed to be collected to refine the models for specific systems.

It is difficult for government organisations and scientists to justify alien tree removal and rehabilitation; unless a known hydrological benefit can be demonstrated. Because invasive trees, particularly those in riparian zones, are assumed to have a greater water-use efficiency than native trees, Dzikiti et al. (2018*) investigated the water use by invasive ***Prosopis*** spp. compared to co-occurring indigenous ***Vachellia*** karroo trees before and after clearing the invasions. ***Prosopis*** spp. are deep rooted, desert-adapted trees that were introduced to the semi-arid regions of South Africa for fodder, fuel and shade, in the early 19th century. Over the last 40 years, ***Prosopis*** spp. have rapidly spread, particularly along river courses and floodplains where they form impenetrable thickets. This has raised concerns about the impact of these invasions on groundwater resources, especially for groundwater-dependent farmers and rural communities. It was these concerns that led to a three-year WRC project aimed at determining the impacts of ***Prosopsis*** invasions on groundwater. Dzikiti et al. (2018*) showed that while individual trees of ***Prosopis*** spp. did not use much more water than indigenous deep-rooted trees, dense stands of ***Prosopis*** have a considerable impact on groundwater levels. They also found that ***Prosopis*** could adapt to harsh conditions, for example, manipulating available water resources when groundwater levels were high through hydraulic redistribution. ***Prosopis*** abstracted groundwater via its tap roots and deposited it in the shallow soil layers via the lateral roots, while the indigenous ***V. karroo*** could not. The study therefore concluded that the volume of groundwater could be significantly increased through clearing operations of dense ***Prosopis*** stands. Similarly, Dye et al. (2001*) compared water use of wattle-invaded and indigenous riparian plant communities, and recommended that water use of a wider range of vegetation types occurring in areas of the country invaded by alien invasive plants be investigated to improve our understanding of IAP impacts on water use, in comparison to indigenous vegetation.

Apart from increased water use, IAPs cause major ecosystem degradation resulting in biodiversity loss. While WfW control programmes in South Africa actively remove the target invasives, ecosystem recovery requires active restoration interventions (Holmes et al. 2020). The results presented by Jacobs et al. (2017*), who assessed the impact of removal methods of IAPs on fynbos riparian ecosystem function, revealed several mechanisms whereby riparian restoration can be thwarted by interventions meant to achieve positive outcomes for ecosystem services.

Another important aspect of restoration practice is to assess how different IAPS, different densities, and duration of invasion, affect restoration potential. To this end, Everson et al. (2016a*) investigated the water use of indigenous tree species versus introduced tree species; and then determined how natural forest species become established within invader plant stands. The study showed that natural forest species have the potential to regenerate in previously forested areas, or to colonise grassland or fynbos within stands of IAPs, challenging the perception that invasive plants prevent regeneration of native species in invaded systems. Furthermore, models of water use results revealed that a significant amount of water can be conserved if alien invaded forest stands are rehabilitated. Using these findings, the study developed guidelines for forest rehabilitation, demonstrating that conversion from invader plant stands into natural regrowth forest is a process that can occur naturally but can also be facilitated by manipulation to benefit the developing natural forest (Everson et al. 2016b).

Not only do riparian invasions affect water quantity and quality, they also have marked impacts on aquatic ecosystem functioning. Alien vegetation in the riparian zone can affect water temperatures through alteration of instream flow rates, degree of shading (especially in first- or second-order streams), channel modification, and changes to natural sediment loads, which have significant consequences for the physiological and ecological functioning of aquatic organisms. Rivers-Moore et al. (2015*) examined the costs of clearing alien riparian vegetation relative to the ecological benefits, as assessed by convergence of water temperatures to target values, of the freshwater systems in the Garden Route Initiative planning area. The aquatic ecosystems in this area are known for their rich Gondwanaland relic aquatic macroinvertebrate communities, which are of significant conservation value because of their vulnerability to thermal changes. Although clearing of alien riparian vegetation, and restoring riparian zones to a desired state will theoretically restore flow and, therefore water temperature regimes, the study showed that thermal regimes were relatively consistent across rivers, irrespective of densities of alien riparian vegetation. Using the results of the ecological study, Rivers-Moore et al. (2015*) suggested that the most cost-effective clearing techniques in terms of financial efficiency and ecological returns could be estimated, and used at a national level towards prioritising areas for future IAP clearing. Simaika et al. (2018*) also conducted research towards developing a tool to quantify and monitor stream restoration success following removal of riparian IAPs. They concluded that although vast amounts of money are spent on clearing invasive alien plants such as ***Acacia mearnsii***, touted as one of the worst of invaders, knowledge of their basic ecology is lacking, and suggest that more in depth studies on the ecological impacts of invasive species be initiated.

Aquatic plant invaders and biological control

In addition to funding research into the effects of riparian invaders, the WRC has funded two particularly significant studies on biological control of aquatic weeds. Aquatic ecosystems in South Africa are prone to invasion by several invasive alien aquatic weeds, the most notorious of which is water hyacinth, ***Pontederia crassipes*** (which used to be known as ***Eichhornia crassipes***) (Hill and Coetzee 2017). Until about 2008 however, red water fern, ***Azolla filiculoides*** Lam. (Azollaceae) also wreaked havoc on inland waters, particularly those in the high-lying interior of the country (Coetzee et al. 2011). ***Azolla filiculoides*** was first recorded in South Africa in 1948 from the Oorlogspoort River in the Northern Cape (Oosthuizen and Walters 1961), and by 1999, it was recorded from 152 sites in South Africa, largely in the Free State (Henderson 1999). Prior to control, ***A. filiculoides*** formed dense mats (5–20 cm thick), on dams of up to 10 ha and on slow-moving water bodies, reducing the biodiversity of aquatic ecosystems, with severe implications for all aspects of water utilization (Gratwicke and Marshall, 2001). These effects were considered most severe in the agricultural sector, where siltation of dams and rivers resulted, water quality was reduced, irrigation canals and pumps were clogged, and livestock that were unable to differentiate between pasture land and a weed covered dam drowned (Hill 1997*).

Figure 14. Water hyacinth on the Roodeplaat Dam, Pretoria. (Credit: Lani van Vuuren)

Owing to the adverse environmental and economic effects of the weed, a much-needed biological control programme was initiated with the importation of a weevil, ***Stenopelmus rufinasus***, from Florida, to SA. in 1995. Although WfW is the primary funder of most biological control research in South Africa, the WRC provided funding for this programme (Hill 1997*, McConnachie and Hill 2005*), which is regarded as the most successful biological control programme in South Africa, and arguably in the world, as it has resulted in complete control of the weed in the absence of any other intervention (Coetzee et al. 2011). This project also afforded the opportunity to conduct a cost-benefit analysis of the programme, given the fairly well-defined nature of the ***A. filiculoides*** problem in South Africa, together with the dramatic success of the weevil (McConnachie and Hill 2005*). The benefit-to-cost ratio of the biological control programme was calculated at 2.5:1 for 2000, increasing to 13:1 in 2005 and 15:1 in 2010 as the annual costs of the programme decreased, indicating a significant return on investment into this research.

The second significant WRC-funded study developed an integrated management plan for the control of water hyacinth in South Africa (Byrne et al. 2010*), which has gone some way to improving the control of South Africa's worst aquatic weed. The role of eutrophication and cold temperatures in limiting the success of biological control of water hyacinth were focused on, followed by recommendations for integrating sublethal doses of herbicides to enhance biological control. The study demonstrated that water hyacinth is difficult, if not impossible, to control with biological control alone in systems where the phosphate concentration is above 0.1 mg/ℓ, and that winter-induced mortality of control agent populations allowed water hyacinth populations to increase early in spring in their absence. Integrated control using glyphosate-based herbicides with biological control was recommended to maintain and encourage agent populations which could suppress the weed's growth in summer. These recommendations were based on findings by Ueckermann and Hill (2001*) who suggested that sub-lethal effects of herbicides on natural enemy physiology and on the weed community; spray patterns for herbicide application to allow the highest number of natural enemies to vacate sinking plants; the concepts of leaving refugia for natural enemies; and the re-innoculation of water hyacinth regrowth with large numbers of natural enemies, should be investigated. Byrne et al. (2010*) went on to promote a new approach to biological control, using inundative releases of biological control agents to promote establishment, followed by reintroduction if they are lost due to flooding, frost or interference from herbicide applications. This study has provided the basis for current water hyacinth management practice in South Africa.

Conclusion

Over the last 25 years, the WRC has facilitated active research into the impacts of IAPs at population, community and ecosystem level, which has led to scenario planning, management plans, legislation, and restoration efforts to mitigate the impacts in a water-scarce country. In addition, the research has facilitated the capacity building of a new generation of invasion ecologists, who studied through the NRF-DST Centre for Invasion Biology (based at Stellenbosch University), and the Centre for Biological Control (based at Rhodes University), who have learnt from some of the top scientists in the field, taking South African invasion ecology into the 21^{st} century.

BIOASSESSMENT AND RIVER HEALTH

INTRODUCTION

This section explores the WRC's involvement in, and contribution to, developments in the field of river health evaluation through the practice of bioassessment over the past three decades. The main focus of this section is the WRC's role in the River Health Programme.

River health

The widely-debated concept of river health arose as a way of describing the condition of a river system, based on its ecological functioning. In a scientific sense, 'ecosystem health' is considered to be the equivalent of 'ecological integrity' – the undiminished ability of an ecosystem to continue its natural path of evolution, its normal transition over time, and its recovery from disturbances (Westra et al. 2000). Here, 'natural' refers to state of the system prior to human-induced impacts.

Bioassessment

Two complementary approaches are used in the assessment of water quality in aquatic ecosystems:

- Physico-chemical testing, in which physical variables (e.g. temperature, turbidity, suspended solids) and chemical variables (e.g. pH; electrical conductivity, nutrient, metal and oxygen concentrations) are measured. This direct approach provides a picture of the state of the system's water quality at a point in time.
- Biological monitoring or bioassessment, in which particular groups of aquatic organisms (e.g. fish, invertebrates, riparian vegetation, diatoms) provide a measure of the system's biological 'responses' to physico-chemical change. Biological monitoring and biological endpoints provide the most integrative view of river condition, or river health, and an early warning of the level of alteration of water quality. Note: The terms biological assessment, bioassessment and biomonitoring can be considered to have equivalent meaning and are used interchangeably in this text.

A brief history of bioassessment in river evaluation in South Africa

Prior to the 1980s, South African water quality managers relied primarily on physico-chemical testing to determine the water quality of the resource (Roux et al. 2008*). There was, however, already a long history of studies investigating the relationship between the invertebrate fauna of a river and water quality (Harrison and Elsworth 1958; Harrison 1958a, Oliff 1960, Oliff and King 1964; Allanson 1961; Chutter 1970, 1971). In 1972, Chutter published his work on development of an empirical biotic index, based on macroinvertebrates. In retrospect, this work was ahead of its time (Roux et al. 2008*), and was overlooked by water resource managers in South Africa as it was considered inter alia to be too time-intensive and costly and required expertise in invertebrate identifications.

During the 1980s, international work on biological monitoring of fish communities (Karr et al. 1986) and macroinvertebrate communities (Armitage et al. 1983) in the United States and Britain helped to convince water resource managers that this form of response monitoring could in fact provide valuable and useful information in assessment of water resource condition (Roux et al. 2008*).

By the early 1990s, the then Department of Water Affairs had instituted a policy of pollution control using 'receiving water quality objectives' (the desired quality) for five categories of water 'user': agricultural, industrial, domestic, recreational, and the natural environment (Dallas and Day 1993*). While water quality criteria and guidelines were available for the first four of these, expertise was required to develop these for the natural environment. The WRC funded two projects: ***The effects of water quality variables on riverine ecosystems*** (Dallas et al. 1995*) and ***Water quality for aquatic ecosystems: tools for evaluating regional guidelines*** (Dallas et al. 1998*) – seminal research projects explicitly linking water quality to ecosystem and biotic response. During this time, Dallas and Day (1993*) also wrote a review, funded by WRC, on the effect of water quality variables on aquatic ecosystems. This was updated in 2004 again with WRC funding (Dallas and Day 2004*) and remains one of the most cited documents on water quality worldwide. These and other studies of the late 1980s and early 1990s culminated in the development of National Water Quality Guidelines for Aquatic Ecosystems (DWAF 1996).

Over the same period, Mark Chutter was investigating the applicability of the British Biological Monitoring Working Party (BWMP) approach to the rapid biological assessment of water quality in South Africa. In 1994, a joint workshop between Australian and South African water scientists was organised and held in Cape Town, supported by the WRC and South Africa's Foundation for Research Development (precursor of the National Research Foundation, the NRF). The objective was that each country should benefit from advances the other had made in recent years: Australia in the development of environmental health indicators, and South Africa in the field of river classification systems (Uys 1994).

At the same workshop, Chutter presented his rapid method for assessing water quality using aquatic macroinvertebrates, based on the BWMP, and entitled the South African Scoring System (SASS) (Chutter 1994*). SASS was extensively tested in several regions within South Africa by a number of river ecologists, and supported by two MSc studies: Roux (1993) and Dallas (1995). The SASS Version 5 (SASS5) method remains one of the principal bioassessment methods in broad use in South Africa, and the method has been accredited to ISO standards (Dickens and Graham 2002). SASS has also been regionally modified for bioassessment of rivers in other African countries (Dallas 2021) including Namibia: Namibian Scoring System (NASS: Palmer and Taylor 2004*), Tanzania: Tanzania River Scoring System (TARISS: Kaaya et al. 2015) and Zambia: Zambian Invertebrate Scoring System (ZISS: Dallas et al. 2018) and for certain aquatic biotopes in the Okavango Delta in Botswana: Okavango Assessment System (OKASS: Dallas 2009).

A National Aquatic Ecosystem Biomonitoring Programme and the River Health Programme

The field-testing of the various developmental versions of the WRC-funded SASS method, and its application in various domains, led to a broad acceptance among water scientists, resource managers and funders (Ashton et al. 2012*), culminating in the establishment of the National Aquatic Ecosystem Biomonitoring Programme (NAEBP) by the Department of Water Affairs and Forestry (DWAF) (Roux 1992; Roux and Harris 1996). An early focus on river ecosystems led to the establishment of the River Health Programme (RHP) in 1994 as a sub-programme of the NAEBP.

The RHP brought together water scientists, stakeholders, funders and water resource managers from around the country. DWAF was the lead implementation agency while the WRC and then Department of Environment Affairs (DEA) were early partners in its development.

The programme was designed to meet the following objectives:

- to measure, assess and report the ecological state of river ecosystems;
- to detect and report spatial and temporal trends in the ecological state of aquatic ecosystems;
- to identify and report on emerging problems regarding the ecological state of aquatic ecosystems in South Africa;
- to ensure that all reports provide scientifically sound and managerially relevant information for national aquatic ecosystem monitoring (Roux 1997*).

The RHP grew into a national network of implementation and research over the next decade. This was considered significant, particularly in light of the prevailing political and socio-economic climate, the limited financial resources and competing priorities, and the scarcity of appropriately skilled individuals (Roux et al. 2008*).

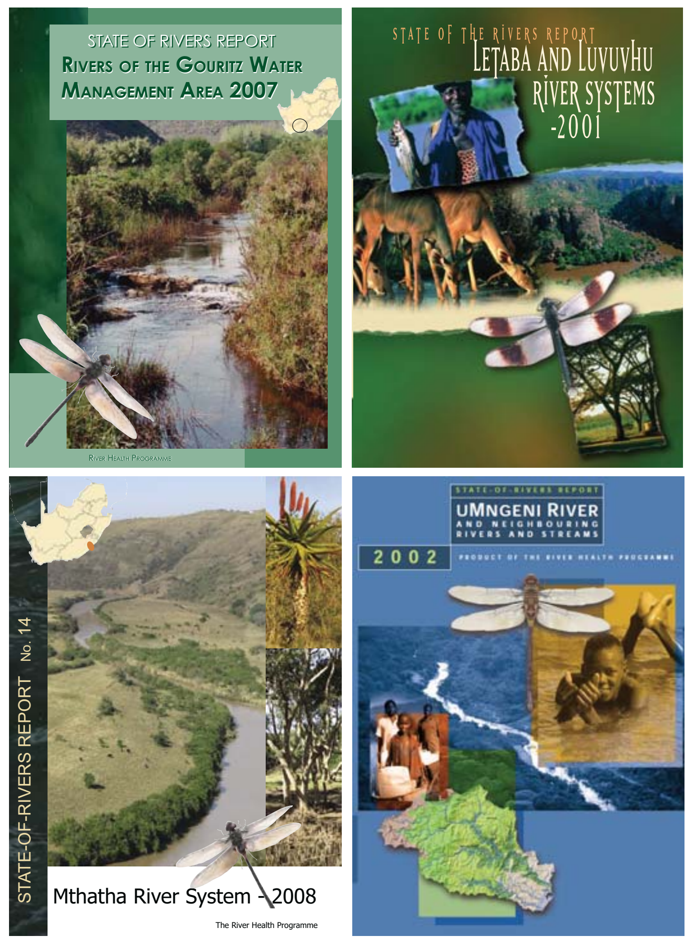


Figure 15. A collection of River Health Programme State-of-River reports.

Visionary research and development

In the early days of programme development, studies were commissioned on the development of a spatial classification of rivers (Eekhout et al. 1996), the selection of monitoring and reference sites (Brown et al. 1996), and a review of and recommendations for ecological indicators for use in the programme (Uys et al. 1996).

Over the years, a suite of indices (listed below) was developed and used for assessment of ecosystem condition, funded by the WRC, DWAF, or other agencies.

- South African Scoring System for macroinvertebrates (SASS) (Chutter 1998*)
- Fish Assembly Integrity Index (FAII) of Kleynhans (1999)
- Riparian Vegetation Index (RVI) Kemper (2001*)
- Habitat Assessment System (IHAS) (McMillan 1998), and later the Integrated Habitat Index (IHI) which included an indirect measure of water quality (Kleynhans et al. 2007a*)
- Ecoclassification manuals (Kleynhans 2007*, 2009*; Kleynhans and Louw 2007*; Kleynhans et al. 2005*, 2007a*, 2007b*; Thirion 2007*)
- Geomorphological Classification System for South African rivers (Rowntree and Wadeson, 1999 a*, b* and a Geomorphological Index (Rowntree and Ziervogel 1999*; Rowntree and Wadeson 2000*)
- Hydrological Index (HI) (Hughes 2000)
- Diatom index (Harding and Taylor 2011*)
- Protozoan index, was investigated but not developed into an index (Joska et al. 2005*)

The biotic indices used in the implementation of RHP remained those based on invertebrates, fish and riparian vegetation, together with the habitat indices for assessing instream and riparian habitats. The other indices listed here were developed further and used in management-related procedures such as the environmental flow requirement (EFR) methodologies, discussed elsewhere.

The RHP was formally implemented in 1997. Resources and technical requirements necessary to implement and maintain the RHP at a national level were compiled in an Implementation Manual (DWAF 2008). This covered all aspects of the RHP – data acquisition, data management and storage, information generation and dissemination, and governance; and essentially provided a map and toolbox for getting RHP going in a region.

In order to meet the National-level objective of 'determining the ecological state of the environment relative to a minimally impacted state within the same river type', the RHP assessment philosophy was founded on the concept of ecological integrity, benchmarking systems against their 'natural' state (or reference condition). The health of a system would thus be ranked by the extent of its deviation from its reference condition at an agreed location and point in time (Roux et al. 2008).

Dallas (2000a*, 2002*) did much of the early work in the development of reference conditions, including a PhD on the subject (Dallas 2001). The study by Dallas formed the basis for the development of SASS interpretation guidelines for the RHP (Dallas 2007c).

At the same time, Dallas and colleagues were establishing the national Rivers Database to serve as a centralised, standard facility for the site information and data collected in biomonitoring for the RHP (Fowler et al. 2000*). The final version of the Rivers Database, released in 2007 (Dallas et al. 2011) formed an integral part of the RHP until 2015, when due to institutional procurement issues and lack of funding for its maintenance, it became non-operational. Recently, the extensive SASS and associated water quality data housed in the legacy Rivers Database have been remobilised into the Freshwater Biodiversity Information System or FBIS (https://freshwaterbiodiversity.org/), developed with international funding from the JRS Biodiversity Foundation (Dallas et al. 2021). Access to legacy datasets such as the Rivers Database and the Biobase (Dallas et al. 1999*) – a database of riverine macroinvertebrate and physico-chemistry data from historical studies in the 1950 to 1990s – is vital for monitoring, managing and protecting freshwater ecosystems.

Aligning the RHP with the 1998 National Water Act

The National Water Act (Act no. 36 of 1998) includes the requirement for the determination of the Ecological Reserve through EFR studies; setting of Resource Quality Objectives; and a Classification System for water resources (i.e. aquatic ecosystems supporting "significant" quantities of water). The information supplied by the RHP was not suitable for these purposes, nor for informing management decisions (Driver 2015). Towards the end of 2003 a review of the design of the RHP began, with the intention of aligning the design of the programme with the requirements of the 1998 National Water Act and with DWAF's Strategic Framework for National Water Resource Quality Monitoring Programmes (Roux et al. 2008*). This process also aimed at formalising programme governance at regional and national levels, developing a national monitoring plan, and revising procedures for quality control. By this time the Programme had grown into a national network of research and implementation activities (Roux et al. 2008*).

WRC outputs from the RHP

For WRC as a co-funder and custodian of the RHP, the major outputs were the WRC reports of relevance to the programme, of which Roux et al. (2008*) listed a certain 24 and possibly more, many of which have been referred to in this chapter.

Another contribution made by WRC, CSIR and other agencies supporting the RHP was in the production of 14 ***State of the Rivers*** (SoR) reports and posters for selected rivers around the country.: These were full-colour, glossy summaries of biomonitoring outcomes at the level of the catchment, i.e. covering entire river systems. These publications were popular and highly effective in bridging the gap between science and civil society.

Training courses in Biomonitoring, SASS5 and Ecostatus Determination were developed and presented either by independent practitioners or by DWAF personnel. Numerous peer-reviewed papers were published, presentations were made at conferences, and a large number of popular articles information brochures and guidelines were produced. A suite of educational resources including a mini-SASS protocol were (Graham 2007*), enabling a transfer of this biomonitoring method to school-goers and also to community volunteers.

Since 2008 the WRC has continued to fund research projects directly or indirectly aligned with the fields of bioassessment, including work in the KNP on frogs (Vlok et al. 2012*); a technical and implementation manual for the National Freshwater Ecosystem Priority Areas (NFEPA) project (Nel et al. 2011a*,b*; Driver et al. 2015); the adaptability and vulnerability of riverine organisms to climate change and the development of tools for assessing biological effects (Dallas et al. 2015*); and research on the use of periphyton as indicators (Ewart Smith et al. 2018*).

The impact of WRC research in support of the RHP

In 2008, Roux et al. were funded by the Commission to assess the impact of research funded by the WRC in support of the RHP. This task was complicated by the fact that many of the developments funded to meet RHP objectives already had a far broader reach and life than the RHP, and that many of the RHP outputs had been co-funded by the WRC as one of several custodians of the programme. The assessment included an assessment of both research excellence (using peer review and research uptake criteria) and research relevance (qualitatively assessed).

The highest ratings were received for flexible management on the part of WRC, the capturing and sharing of knowledge, the broad influence of the RHP, and the achievement of RHP-specific objectives. 'Acceptable' ratings were returned for diversity of participation, continuity over time, increase in capacity and awareness, and adoption by implementers. Lower ratings were achieved for international research collaboration, research excellence, and the lack of evidence of improvement of river health and of effect on the water policy environment over the period of the programme (although in fairness these outcomes were never part of the programme objectives).

The WRC's participation in this field has undeniably yielded more-than satisfactory outcomes. The objectives of the RHP did not include the actual improvement of river condition. Setting this objective for even a single river is the task of river restoration, which is written about in Chapter 8, and meeting it will require clear intention and tenacity on the part of the various role players involved.

Ecosystem services and natural resource economics

Ecosystem services can be defined as the benefits humans obtain from the ecosystems of the Earth. They include 'provisioning' services such as drinking water and plants; they provide 'regulating' services such as clean air and decomposition of waste, non-material 'cultural' services such as spiritual and recreational sites, and 'supporting' services that allow the world to function: photosynthesis, the water cycle, and so on. Another commonly used term, ***natural capital,*** refers to the Earth's resources such as minerals, arable land and fossil fuels, and processes such as waste assimilation, temperature regulation and the regeneration of oxygen. Natural ***resource economics*** examines the connections and interdependence between human economies and natural ecosystems. These two fields together aim to identify the benefits that humans obtain from Nature and, as far as possible, to quantify them and assign them a monetary value. When it is possible to provide quantification in monetary terms, the real value becomes apparent to civil society and political decisions based on the perception of natural ecosystems as 'wastelands' can be adjusted in the face of environmental and economic realities. A remarkable analysis of the global value of ecosystem services, and the loss in value since the turn of the twenty-first century, is provided by Costanza et al (2014).

DH notes that he first encountered the general field of ecosystem services (ESs) and resource economics in 1992 when, with support from the WRC, he and his colleagues convened what was effectively a beginners' workshop in resource economics. The field has expanded since then, with some 25 WRC-funded reports being completed between 2002 and 2017. Here we briefly describe some of them.

Economic value of ecosystems

An early study by Palmer et al (2002*) provided an ecological and economic evaluation of wetlands in the Upper Olifants River (Mpumalanga) Catchment, with the intention of assessing the net economic value derived from these wetlands, and the opportunity cost of conserving them. The authors noted that their study provided a basic framework for a management plan for the wetlands, but that more detailed studies would be needed to understand the key drivers, functions, biodiversity values and uses of each wetland type. This is an example of excellent preliminary work being funded but follow-up funding being inadequate or non-existent and thus negating a lot of the value of the initial studies.

Several reports examined the opportunity cost of degraded aquatic ecosystems and the costs and benefits of their restoration, and indeed this is a major use of ESs. The work of Blignaut et al (2012*) was designed to estimate the value of restoring a number of degraded ecosystems around South Africa. The authors focused on developing an evidence base to support economic tools involved in cost-benefit analyses regarding whether or not to restore a degraded site. They note, somewhat ruefully, that understanding the ongoing problem of degradation "fails to change the economic drivers that generate the need for restoration … largely because the cost of degradation and the need for, and value of, restoration are not explicitly considered." This valuable report includes a number of Policy Briefs discussing, for instance, implications of the regulatory landscape for the restoration of natural capital; urban water use; and market challenges for the restoration of the natural environment.

Figure 16. A view over the Baviaanskloof, which was used as a case study in De Lange et al's 2017 study.

Using the Baviaanskloof as a case study, De Lange et al (2017*) identified key ecosystem services and their forward linkages, attempting to understand how to improve market access to such services, and creating or improving the value chains in the South African context.

In contrast, ACGE (2017*) studied the Khayelitsha wetlands system, situated in a socio-economically challenged part of Cape Town. They examined the ecosystem services provided to the surrounding communities in a context of socio-economic and spatial disparities in relation to upstream users, before introducing a formal green business-incubation programme for local homeowners. Another project pointing out the value of urban rivers, which are often viewed as being degraded and therefore of little use, was that of Maila et al (2017*), who examined ecosystem services produced by a number of urban river systems, highlighting the trade-offs between value provided by, and impacts on, the urban river.

In another project examining aspects of the relationship between local communities and the wetlands they depend on, Lewis et al (2011*) asked whether the introduction of social welfare grants had resulted in a change in the perceived value of, and associated behavioural responses to, wetland ecosystem services by local households. Their results were disturbing. After the introduction of social welfare grants, the value of wetland services appeared to be locally perceived as low, regardless of resource scarcity, access to alternatives or the amount of time a household has available for agriculture and resource-based activities. The authors noted that the shift to a cash-based economy, and the consequent decreasing dependency on the wetland for provisioning services, may result in a reduced incentive to manage it. This result is an interesting contrast to that of Lannas & Turpie (2010*), who compared wetland use in a rural wetland in Lesotho, and Mfuleni, a peri-urban wetland in an informal settlement in Cape Town, finding that both were highly valued by the people depending on them; the monetary value of the wetland to individuals was three times as great in the Mfuleni wetland as in the Lesotho wetland, despite the fact that Mfuleni is a degraded wetland in an informal settlement.

A number of useful handbooks and guides have been written by WRC-funded authors. These include ***A guideline for the comprehensive valuation of aquifers and groundwater*** by Pearce et al (2014*); ***Linking property rights, ecosystem services and water resources: an introduction*** by Hay et al (2013*); and ***Estuaries, economics and freshwater: an introduction*** (Hay et al 2010*) while Pollard and colleagues (Pollard 2013*) have developed a participatory framework for understanding water-related ecosystem services within the context of Classification and the Reserve.

Two models have been developed, assisted by WRC funding: a Decision-Support Model for ecosystem services in the light of adaptation to climate change (Mitchell et al 2014*) and a generic model to assess the costs associated with eutrophication (Graham et al 2012*). This model once again provides a way of setting the cost of a perturbation against the cost of the remedy: quantification of the costs associated with eutrophication will assist researchers and policymakers in identifying the appropriate policies required to address eutrophication problems in South African river systems.

With regard to specific ecosystem types, the Eastern Cape Estuaries Management Programme led by the Institute of Natural Resources, in partnership with the WRC, the (then) national Department of Environmental Affairs and Tourism and the University of KwaZulu-Natal (UKZN) focused on the ecosystem service provision of estuaries and how these might be translated into real economic opportunities (e.g. Breen et al 2004;* McKenzie & Hay 2005*; Hay 2007*; Bowd et al. 2011*). A similar, more recent WRC-funded programme led by UKZN, focused on the tangible benefits that wetlands might yield (Hay et al. 2013*).

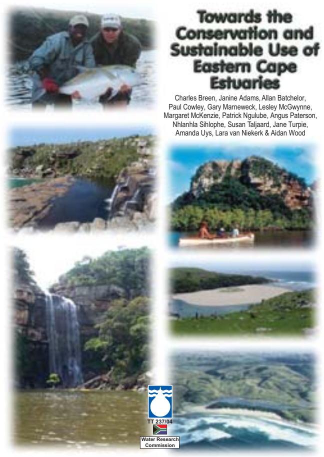


Figure 17. One of the reports published under the Eastern Cape Estuaries Management Programme.

Figure 18. The well-studied Knysna estuary. (Credit: 123RF stock photo)

In the last 15 years or so, though, a greater emphasis has been placed on ecosystem services provided by wetlands. In 2009, Kotze et al (2009a*) developed an assessment tool known as WET-EcoServices (updated version Kotze et al 2020*) for rapidly assessing ecosystem services supplied by wetlands, thereby aiding informed planning and decision-making. It provides guidelines for scoring the importance of a wetland in delivering a number of different ecosystem services, including flood attenuation, sediment trapping and the provision of livestock grazing. Such a tool provides a useful rapid method for qualitatively evaluating the ecosystem services of a wetland and was the forerunner of a number of other assessment tools described below.

Some years ago, the WRC funded the Wetland Health and Importance (WHI) initiative as part of the National Wetlands Research Programme. Some of the work of the programme was to develop or improve on bioindicators of ecosystem condition, while others dealt specifically with ecosystem services and resource economics. Of these, the first (Turpie et al 2010a*) provided a very useful review of the wetland valuation literature. The second (Kotze et al 2010*) assessed the environmental condition, ecosystem service provision and sustainability of use of two wetlands in the Kamiesberg uplands in an arid and economically depressed part of the Northern Cape, partly by using WET-EcoServices (see above). This work was designed partly to feed into a tool for the assessment of the value of wetlands for livelihoods, which was being developed as part of the same project (Turpie et al 2010b*). The aim of this study was to develop a simple index for the assessment of a wetland's importance to people's livelihoods through understanding the level of dependence of surrounding communities on the wetland. The tool outlines the way in which the index parameters are estimated at a rapid, intermediate, or comprehensive level, depending on the budgetary constraints or the level of confidence required. Since the index produces a result which is in comparable units, the results can be used to assess the relative importance of a wetland compared to others in the catchment or even nationally, and to rank, or prioritise, different wetlands in terms of management priorities. It would also be possible to apply the index when investigating the implications of different future scenarios (e.g. changes in wetland property rights, climate, and population density). The index developed here can be used in conjunction with existing South African indices such as WET-Health, WET-EcoServices and WET-SustainableUse developed during the WRC's Wet Management Programme. A second tool, also developed during the WHI programme by Turpie & Kleynhans (2010*), provides a protocol for the quantification and valuation of wetland ecosystem services.

Finally, as part of the WHI programme, Turpie and colleagues

(Turpie 2010*) performed a number of case studies aimed at filling some important gaps in wetland valuation techniques. This included the study by Lannas & Turpie (2010*) described above. Kleynhans et al (2010*) investigated flood attenuation and the maintenance of base flows in Nylsvley, a large valley-bottom wetland in Limpopo Province. Turpie et al (2010c*) attempted to valuate the water treatment function of wetlands. Altough confidence limits were very wide, the study did indicate that the average value of the water treatment service provided by wetlands in the study area was about R14 350 ± R12 385/ha/y. Lastly, Skovronik & Turpie (2010) estimated the value of tourism in the Nylsvley floodplain to be in the order of at least R9-10 million per annum. Each of these results was interesting, and an important development in the study of resource economics.

Summary

Fast forward to 2021. How far have we advanced from those early days of exploration? I (DH) suggest we have come a long way, exemplified by this quote from two of South Africa's leading resource economists, Douglas Crookes and James Blignaut: "… restoration can no longer be considered as merely a cost item on an expenditure account of a company or government, but truly as an indispensable investment in the future of both people and the planet." (Crookes and Blignaut 2019). What this indicates, to me anyway, is that the science is progressing, that methodologies are becoming increasingly sophisticated and that the results are able to inform both policy and practice.

Nonetheless, it seems that not a single report has been published on the topic since 2017 and the resource economics of natural systems do not appear to be a WRC priority. The gradual de-emphasising research into natural systems and their management is evident here and elsewhere. It is of considerable concern that few – or perhaps no - studies are being undertaken in this critically important field.

GUIDELINES FOR ECOSYSTEM MANAGEMENT

INTRODUCTION

South Africa's growing population, urbanisation, and industrialisation and the legitimate expectation of the majority for an elevated standard of living, are creating increasing demands for water and imposing increasing stresses on aquatic ecosystems (King and Pienaar 2011*). Although South Africa has a world-class water act that ensures the protection of our aquatic ecosystems, but its implementation is lagging behind. The WRC has funded numerous projects to develop tools to ensure the effective management of our freshwater ecosystems. The responsibility for conserving South Africa's water ecosystems is shared between different government departments and societal sectors, frequently resulting in an overlap of mandates (Roux et al. 2006*). In a WRC-funded report, Allanson (1995*) provided a summary of freshwater ecosystems in South Africa and provides the reader with an ecological approach to water resources management (WRM) and guidelines for planners and managers.

The contribution of WRC to management guidelines

The general complexity of freshwater ecosystem management, and the associated unpredictability, demands participative, sensible, effective coordination (e.g. Wepener 2001*). Roux et al. (2010*) developed a set of guidelines to assist those responsible for the management and conservation of South Africa's freshwater ecosystems. These guidelines suggest practical steps that might facilitate purposeful learning and adaptation process for achieving appropriate ecosystem management. Guidelines to integrate wetland protection, conservation and management into catchment management planning were developed to chart a way through the complexities, enabling responsible agencies to incorporate wetlands into their catchment management planning processes. As part of this initiative Dickens et al (2003*) developed a template that could be used in implementing wetland management.

Figure 19. The set of buffer zone tools published by the WRC in 2017.

Macfarlane et al. (2014*) developed preliminary guidelines for assessing appropriate buffer zones for rivers, wetlands, and estuaries. A set of buffer zone tools was developed to provide the user with the primary tool for assigning appropriate buffer zones, The tools highlight the complete process to be followed. These preliminary guidelines were subsequently updated and documented in two WRC reports (Macfarlane and Bredin 2017a*, 2017b*). Macfarlane and Bredin (2017a*) also developed a practical guide to assist users with the hands-on application of the buffer zone tools. It includes field sheets and practical guidance for collecting and interpreting relevant desktop and field information. A range of spreadsheet-based buffer zone tools (Desktop, Rivers, Wetlands, Estuaries) was developed to help users determine suitable size of buffer zones. They also developed a mitigation measure tool as a quick-access point for users with a broad interest in mitigation and those who advise on measures to mitigate impacts of land-use on water resources (Macfarlane and Bredin 2017b*).

The blackfly problem along the lower Orange River has received funding from the WRC since the 1990s, starting with research on the chemical and biological control (Palmer 1995) and developing principles for integrated control of blackflies (Palmer 1997*). This early research was later extended resulting in the development of guidelines for the integrated control of pest blackflies (Palmer et al. 2007*) and culminated in the development of a predictive management tool for blackfly outbreaks (Rivers-Moore and Palmer 2019*).

The difficulty in managing wetlands to the best advantage and wellbeing for different users prompted the development of Decision Support Systems to rapidly assess the ecosystem services provided to the users of wetlands in South Africa (Kotze 2014*). It builds on WET-Ecoservices (Kotze et al. 2009*) and the system for estuarine wetlands (Bowd et al. 2011*). To determine the Present Ecological State (PES) of wetlands, Ollis et al. (2014*) developed two decision-support tools. The first is a generic flowchart -based framework, which is a stepwise process to identify, delineate, classify, assess, manage, and monitor wetlands. The second tool is a spreadsheet-based decision-support protocol for the rapid assessment of the PES of wetlands, while Driver et al. (2011*) compiled an implementation manual on use of the WRC-funded Freshwater Ecosystem Priority Area (FEPA) maps. This manual also includes ecosystem management guidelines for River, and Wetland FEPAs, sub-quaternary catchments associated with river FEPAS, and upstream management areas. See Chapter 10 for a more detailed treatment of WRC-funded wetlands research.

One of the strengths of WRC-funded research is the useful documentation that often accompanies the work. The guidelines and protocols for ecosystem management are some of the most useful.

Where to from here?

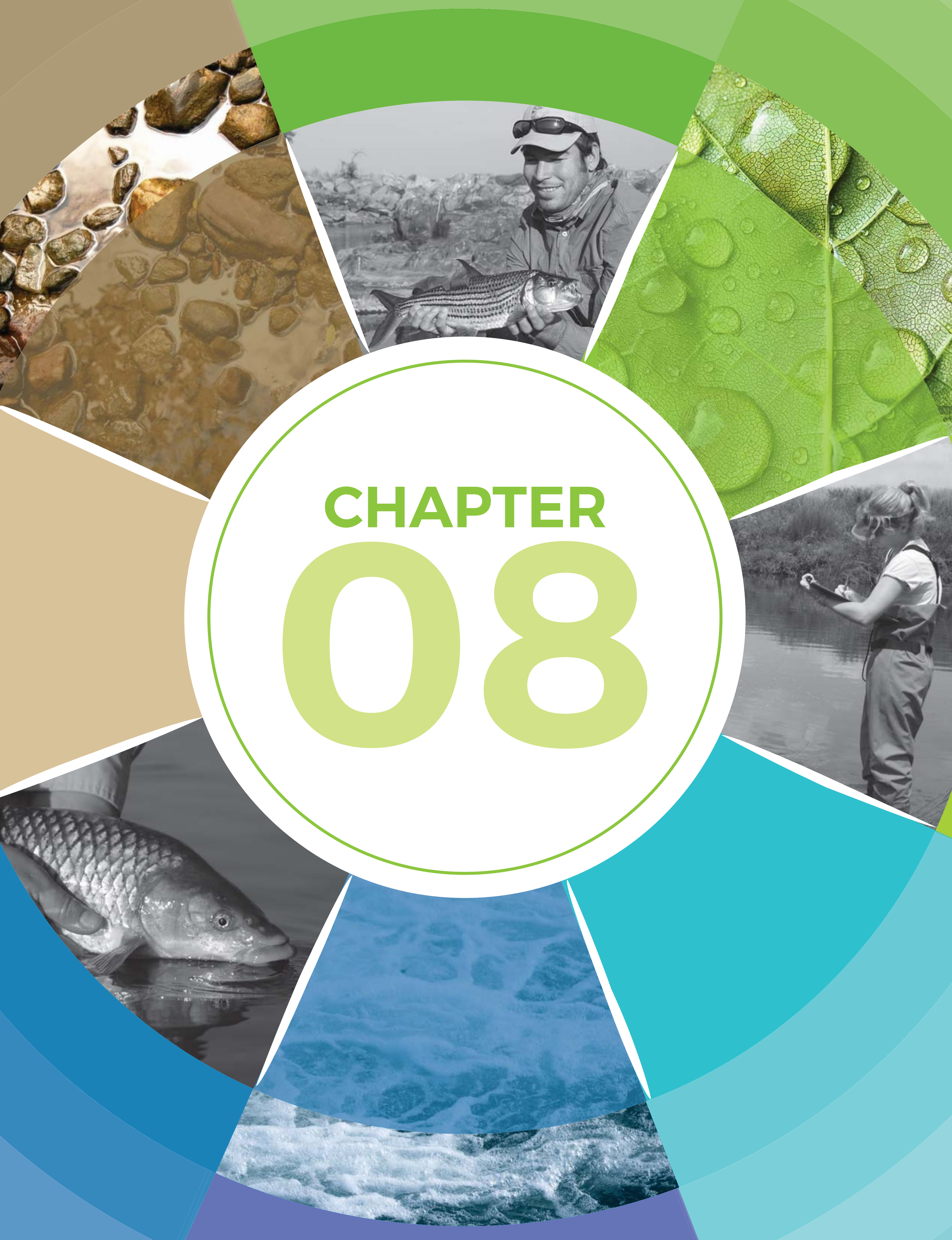
The WRC has been instrumental in advancing our understanding of freshwater ecosystems and has contributed enormously to their management in South Africa, including the development of a tutored Master's and short-term learning programmes in environmental water requirements (Wepener 2016*). There is always more to do, however, and a number of recommendations by the authors of this chapter are collated here.

In the future, as collecting effort increases, and new species are identified and described, the WRC identification guides will become outdated. It is to be hoped that the WRC will encourage young systematists to contribute to biodiversity science by updating these volumes or contributing new ones to this valuable resource Furthermore, much of the existing baseline data (for example species distribution lists and checklists for different regions) that underpin our understanding of the ecology of freshwater ecosystems, remains undigitised, and in danger of being lost. It is excellent news that the WRC is currently initiating a project to warehouse the huge amounts of data generated by WRC-funded projects over the years.

The lack of research into taxa other than freshwater fish is also somewhat alarming, as the loss of freshwater biodiversity is a significant issue in South Africa. The first IUCN Red List Index for freshwater-associated taxonomic groups in South Africa revealed an elevation in their threat status over time, and an increased risk of extinction for most members of the freshwater fauna (Skowno et al. 2019). South Africa is also a signatory to a number of international conventions and treaties for the conservation and protection of biodiversity, including the Convention on Biological Diversity (1994), and the loss of biodiversity is in direct contravention of our commitment to this convention. In addition, the South African National Biodiversity Strategy and Action Plan (NBSAP) and the National Biodiversity Framework (NBF) legislate the requirements for the management, conservation and sustainable use of biodiversity (Skowno et al. 2019). While these organisations are responsible for the management of biodiversity in South Africa, they are not in a position to fund water-related research. For this reason, we recommend the fuunding of fundamental research on the ecology and biodiversity of our freshwater ecosystems. More specifically, attention needs to be paid to the description, cataloguing and assessment of existing biodiversity, including taxonomic surveys, genetics, life histories, species distribution and population trends of existing taxa. Implementation of effective monitoring plans is also crucial, perhaps using citizen science, as has been used effectively elsewhere.

Regarding biocontrol and the management of aliens, strategic research is needed into the ways in which the processes underlying the provision of ecosystem services are affected by invasive alien plants and their management in riparian environments. This is especially important when considering the major national investment in the restoration of ecosystem services through the WfW programme.

Regarding the field of ecosystem services and resource economics, we recommend that the WRC develop a clear, strategic direction for research into these topics, which should be afforded high priority. There has been very little research in these fields over the past few years, even though they are critically important, particularly in the context of the myriad challenges we face regarding management of water resources and the ecosystems they support. We recommend that the WRC re-energise this research focus internally by establishing the necessary capacity, establishing a clear strategic direction, and securing the services of leading local expertise.



CHAPTER 08

THE WRC AND RIVERS, RESERVOIRS AND THE RESERVE

Belinda Day, Jenny Day, Liz Day, Rob Palmer, Karl Reinecke, Kate Rowntree, and Christa Thirion

INTRODUCTION

This chapter deals specifically with Water Research Commission (WRC)-funded research relating directly to riverine ecosystems, rather than freshwater ecosystems in general. Other, broader aspects of the management, functioning, biodiversity and conservation of freshwater ecosystems (i.e. those that encompass rivers, wetlands and estuaries) are included in the general Ecosystems chapter (Chapter 7).

A brief history of the WRC's involvement in South African river research

Understanding the ways of South Africa's rivers began in the 1950s, when Arthur Harrison, Marjorie Scott and Jack Elsworth undertook a detailed study of the Berg River in the south-western Cape (e.g. Harrison & Elsworth 1958) under the auspices of the National Institute for Water Research (NIWR) of the Council for Scientific and Industrial Research (CSIR). At the time, when limnological work worldwide was focused on lakes, this study was a groundbreaking introduction to the ecology of rivers. A little later staff of the NIWR also worked on a number of Natal rivers, including the Tugela (e.g. Oliff 1960), the Umgeni and the Jukskei (Allanson & Gieskes 1961) as well as the Vaal in the then Transvaal (e.g. Chutter 1970). A hiatus in ecological research on rivers followed, with most work being focused on reservoirs and, a little later, on water requirements for ecosystems such as the Pongola floodplain (Heeg and Breen 1982). River research was revived in the early 1980s by Jackie King's PhD thesis (King 1982) and expanded, in 1984, by the newly instituted Freshwater Research Unit at the University of Cape Town and the Kruger National Park Rivers Research Programme, which started in 1988 (King & Pienaar 2011*).

It was only in 1990 that the WRC began funding 'ecosystem' studies, that included studies on rivers (WRC Annual Report, 1989*, and see Chapter 7). Although WRC-funded work has since contributed enormously to our understanding of river ecology in South Africa, our knowledge has largely been a serendipitous offshoot of very practical research into river management. In this chapter we look first at the WRC's contribution to the study and management of fluvial geomorphology (Kate Rowntree) which, together with flow, determines the physical structure of rivers. This is followed by a section on Instream Flow Requirements (IFRs) (Christa Thirion). An increased recognition, during the 1980s and 1990s, of the importance of providing sufficient water for rivers to maintain ecosystem functioning, led to the development of this discipline. Methods of determining IFRs were developed through research funded by the WRC in conjunction with the then Department of Water Affairs (DWA). A discussion on the WRC's contribution to our understanding of the riparian zone with its associated vegetation follows (Karl Reinecke). Then, because the exploitation of rivers in water-scarce countries such as South Africa invariably results in the construction of large numbers of impoundments (reservoirs, or dams), a section follows on the WRC's contribution to the functioning, management and ecological effects of reservoirs (Rob Palmer). Discussions on the research and management requirements of urban rivers (Liz Day), as well as the rehabilitation of degraded river ecosystems (Liz Day), end the chapter.

Geomorphology

Geomorphology is the study of landforms and their processes, forms and sediments. In this chapter we are concerned specifically with fluvial geomorphology, which is the study of the interactions between the physical shapes of rivers, their water and sediment transport processes, and the landforms they create. Catchments, which deliver water and sediment to the channel, are also key components of the fluvial system. As a catchment's water resources are developed and exploited, changes to the flow and sediment regime result in reciprocal changes to channel morphology and associated aquatic and riparian habitat. Fluvial geomorphology is therefore recognised as a key driver of river ecosystems. In response there has been a growing interest globally in the application of geomorphological principles to river management (Thorne et al. 1997, Brierley and Fryirs 2000, Newson and Sear 2001).

The significance of geomorphology to sustainable river management was recognised by the WRC in the mid-1990s when the geomorphology of a number of South African river systems was investigated. The recognition by the WRC of the broader importance of fluvial geomorphology is evidenced by the commissioning of a popular guide to geomorphological science and its application by Freeman and Rowntree (2005*).

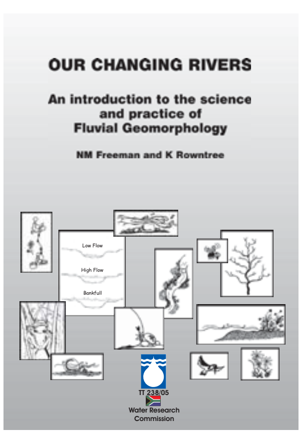


Figure 1. The popular guide to geomorphological science by Freemand and Rowntree that was published in 2005.

The Kruger National Park Rivers Research Programme

The Kruger National Park Rivers Research Programme (KNPRRP), initiated in the late 1980s, provided valuable support for geomorphological research in the Sabie and Letaba rivers. The integrated nature of the programme allowed geomorphologists to collaborate with ecologists and engineers in order to gain a better understanding of the rivers' ecosystems and to provide guidance to managers. The geomorphological response to changing flow regimes in the Sabie and Letaba rivers was investigated by Heritage et al. (1997*). In another WRC-funded project, Heritage et al. (2000*) developed a system for characterising representative river reaches in order to describe the complex geomorphology of the Sabie River, with its alternating bedrock and alluvial sections. The information generated by these projects was developed further by Birkhead et al. (2000*) who designed a geomorphological change model for the Sabie River. The linkages within the Sabie River ecosystem were recognised both as a result of a 1997* study by Broadhurst et al. on the hydraulic resistance of reed beds, which have a profound effect on sediment deposition and bar formation, as well as the development by Jewitt et al. (1998*) of a model of abiotic-biotic links. James et al. (2002*) then furthered the research on reed bed interactions. The geomorphological research funded by the WRC laid the foundation for further studies in response to extreme flood events in 2000 and 2012 (Entwistle et al. 2015; Milan et al. 2018). This research underlined the importance of extreme events in resetting the river system, noting also that smaller, more regular floods continually recreate a complex morphology of benches and bars (Birkhead et al. 2000*).

Figure 2. The Sabie River in flood. Through the erosion, transport and deposition of sediment, floods shape the channel morphology that provides habitat for river organisms. (Credit: KM Rowntree)

Geomorphological classification

Geomorphologists tend to look at broader scales of time and space than do ecologists. A pebble on a riverbed is part of a larger cluster that makes up a sedimentary bar, part of channel-reach morphology. A length of channel is made up of a number of reaches, each with a distinctive form. Together these reaches comprise the river system, contained within its catchment. What happens at each of these spatial scales, and their interaction in time and space, is important for understanding geomorphic processes. A pebble can change its location within minutes, bars can take days to years to change their form whereas reach morphology is likely to respond to decadal changes in flow. The structure of a drainage network is imprinted on a landscape that has evolved through millennia of geological time. This conceptual understanding of time and space scales was formalised through the development of a hierarchical river classification system by Rowntree and Wadeson (1999*) and a related hierarchical classification was developed for the Kruger Park Rivers by Heritage et al. (2000*).

More recently Cullum and Rogers (2011*) presented a framework for the classification of drainage networks in savanna landscapes that specifically links hillslopes and channels within a hierarchical framework of patch dynamics that stresses the links between water, vegetation and hillslope processes. All three classification systems (Rowntree and Wadeson 1999*; Heritage et al. 2000*; Cullum and Rogers 2011*) were designed to identify relevant links to ecosystem processes at different spatial scales. At the broader scale, Rowntree and Wadeson (1999*) proposed a scheme of river zonation to characterise the progression of channel types down the length of a channel in response to changes in gradient that can also be linked to related changes in river habitat and therefore the biota. At the lowest level, the classification system described hydraulic biotopes that link habitat patches to flow type as a function of the interaction between channel morphology and flow volume. The hydraulic biotope classification was developed in collaboration with geomorphologist Professor Malcolm Newson from Newcastle University and ecologist Dr Jackie King from UCT (Rowntree 1996*). Its application as a habitat mapping tool was explored further by Wadeson and Rowntree (2005*) and its ecological relevance was tested by King and Schael (2001*). In a parallel process, engineers developed hydraulic models to infer habitat variability (e.g. Jordanova et al. 2004*). These concepts and methods are now entrenched in the suite of methods used by the South African Department of Water and Sanitation (DWS) for assessing environmental water requirements.

Figure 3. Flow type and substrate define hydraulic biotopes in the Tsitsa River. (Credit: KM Rowntree)

Channel processes

The WRC has funded a number of projects, both by geomorphologists and engineers, that looked at channel processes and the responses of the channel to changing flow and sediment regimes. Important contributions were made during the KNPRRP as reported above (e.g. Heritage et al. 1997*; Birkhead et al. 2000*). Flood events are the key drivers of channel form, so any impact on floods due to upstream water-resource developments can cause major changes downstream. Beck and Basson (2003*) investigated the impact of dam development on river morphology, while Dollar and Rowntree (2003*) investigated channel-forming discharges in the unregulated Mkomazi River and the regulated Mhlatuze and Olifants rivers. Together, their research supports the globally accepted notion that the active channel approximates the "bank-full" channel of earlier studies and is formed as a response to floods with recurrence intervals of between one and seven years, depending on channel type, while the macro-channel is related to floods with a ten- to twenty-year recurrence interval.

Bankfull discharge has been found to be related not only to the morphology of the cross-section but also to other channel features, such as the spacing of pool-riffle sequences, which are also related to discharge frequency. Jonker (2002) found that the geometry and particle size distribution of pool-riffle sequences in cobble bed rivers of the Western Cape could be related to shear stresses during bankfull discharge, with recurrence intervals of between 1 and 3 years.

While the impact of river regulation due to impoundments has been widely investigated globally, less attention has been paid to the impact of inter-basin transfers. Rowntree and Du Plessis (2003*) reported on the massive widening and deepening of a first-order channel that was subject to an inter-basin transfer from the Fish River to Sundays River.

Riparian vegetation has a close relationship with channel-bank morphology and can be both a response (Mackenzie et al. 1999*; Botha 2001*; Reinecke and Brown 2013*) and a driver (Rowntree and Beyers 1999*). The response in more humid environments depends on the relationship between flood frequency and channel form (Botha 2001*; Reinecke and Brown 2013*) whereas in semi-arid environments, such as occur in the Kruger National Park, it is infrequent events that create new sites for the establishment of individuals, rather than the more frequent, smaller floods, that are the overriding influence (Mackenzie et al. 1999*). Woody vegetation is known for its stabilising influence, but invasive alien vegetation can cause instability and channel widening, as reported by Rowntree and Beyers (1999*) for channels invaded by black wattle. Riparian vegetation is discussed further in this chapter.

Figure 4. Sand banks in the Sabie River provide habitat for reeds, which protect the sand from erosion during moderate flood events (Credit: KM Rowntree)

Sediment and ecosystems

While floods represent the key drivers of the geomorphic processes that shape channel form, the availability of sediment in grades ranging from boulder to silt provides the material from which the channel is structured. The primary source of sediment is the catchment, with secondary sources from channel banks and upstream channel beds. While coarse sediment (boulders to coarse gravel) is important for providing habitat, the deposition of fine sediment is acknowledged as impacting negatively on habitat quality in many circumstances. An early study by Madikizela et al. (2001*) identified fine sediment, rather than water chemistry, as the main impact on macroinvertebrate composition. WRC reports by Gordon and Muller (2010*) and Gordon et al. (2013*) present water quality guidelines for suspended solids based on research with riverine invertebrates. More important is the sediment that settles out on the channel bed, infilling interstitial spaces. Huchzermeyer (in Van Tol et al. 2018*) investigated the dynamics of fine sediment on the bed of the Tsitsa River, monitoring the response of both sediment and invertebrates to flow. The results of this research are being used to develop a sediment-monitoring tool that uses macro-invertebrate data collected during a SASS5 sampling programme (Huchzermeyer and Rowntree in press).

Figure 5. Deposition of fine sediment impacts negatively on instream habitat, causing infilling of interstitial spaces between coarse sediment and loss of shallow pool habitat. (Credit: KM Rowntree)

Because sediment poses a risk to built infrastructure, including dams, hydroelectric turbines and irrigation pumps, there has been considerable investment by the WRC into research on assessing sediment yield. Modelling, largely by engineers, has had to substitute for a paucity of physical evidence. An early sediment-yield map was produced by Rooseboom et al. (1992*), accompanied by a report on sediment transport processes (Rooseboom 1992*). In 1995* Lorentz and Schulze contributed a sediment module to the ACRU model. The early sediment-yield model by Rooseboom et al. (1992*) was updated by Msadala et al. (2010*), and included an erosion risk map produced by geomorphologist Jay le Roux. Many sediment-yield models are based on predicting erosion by surface wash, ignoring the important role of gullies. More recently Le Roux and Barker (2015*) integrated gully erosion into sediment yield modelling of the Mzimvubu catchment.

The neglect of empirical studies on sediment processes has been rectified to some extent by WRC-funded research by Hill et al. (2019*) and Moodley et al. (2019*). The first study looked at erosion and sediment yield from farming and forestry systems while the second focused on the role of unpaved access roads as sediment sources in forest plantations. In an earlier study, Chaplot et al. (2012*) investigated sediment, nutrient and organic carbon fluxes driven by surface-water erosion in small-scale agricultural landscape of KwaZulu-Natal. The research highlighted the economic and environmental benefits of the practice of no-tillage.

Sediment delivery from hillslopes to channels depends largely on connectivity between different landscape units and the WRC has supported a number of studies that investigated this connectivity. Lorentz et al. (2011*; 2012*) worked in a small catchment where the transport of nitrogen and phosphorus by sediment was an issue, while van der Waal and Rowntree (2015*) looked at connectivity in the much larger catchment of the Vuvu River, a tributary of the Thina River in the Eastern Cape, where erosion is a major concern. All studies applied sediment fingerprinting to identify sources, a relatively new technology to South Africa but widely used globally (Collins et al. 2020).

Figure 6. Gullies in the Thina River catchment provide a pathway for surface runoff and sediment to move from the hillslope to the main channel. (Credit: KM Rowntree)

The importance of an integrated approach to the management of sediment-related risks has been addressed by Jeleni et al. (2013*). Integrated planning for catchment restoration through soil erosion control is promoted through the DFFE funded Tsitsa Project. The WRC 'Green Village' project (Rowntree et al. 2018*) laid the foundation for integrating soil erosion control with business opportunities at the household and village scales, enabling long term sustainability. Households grow vetiver grass plugs for sale to the rehabilitation implementers, while livestock owners are working towards a collective conservation agreement that will open up marketing opportunities for wool and beef. Planning and monitoring of rehabilitation sites has become a joint process involving the implementers, a development NGO and village residents.

Wetlands and estuaries

Wetlands are an important component of the fluvial system and geomorphologists have contributed to our understanding of wetlands and the recommended guidelines for their rehabilitation through a number of WRC projects, including the Wetlands Research Programme: Wetland Rehabilitation (Dada et al. 2007*). Other projects include a study of ephemeral wetlands in the Port Elizabeth area by Schael et al. (2015*) and the Palmiet wetlands of the Krom River in the Eastern Cape by Tanner et al. (2019*). Estuaries are found at the interface of the river and the ocean and are strongly influenced by flows and sediment from the upstream catchment. Bate et al. (2011*) reviewed studies of the Mfolozi Estuary and associated floodplain that illustrated the strong geomorphic underpinnings of floodplain processes driving the system. See also Chapter 9 on wetlands and Chapter 10 on estuaries.

Geomorphology and environmental water requirements

An important outcome of the geomorphic research funded by the WRC is the recognition by the broader research and management community of its role in guiding river management. The science of geomorphology is now embedded in Environmental Water Requirement (EWR) protocols (see elsewhere in this chapter for a detailed discussion on EWRs). The DRIFT user manual (Brown et al. 2005*), for instance, states that the descriptions of the biophysical consequences of flow changes are usually built up in a sequence starting with geomorphological principles. The role of geomorphology in the Building Block Methodology is described by Rowntree (2008*). In 2010* James and King edited a report on ecohydraulics that demonstrated the strong geomorphic underpinnings of river ecosystems, as exemplified by the separate chapters on Pattern and Process in River Landscapes (Ractliffe et al. 2010*), Describing Hydraulic Habitat (Paxton et al. 2010*), and Channel Maintenance Flows (Jonker and Shand 2010*). It is noteworthy that none of these authors is a geomorphologist; yet as ecologists and engineers they had firmly embraced geomorphic theory and its application in South Africa.

The development of assessment indices for the classification of water resources was an important project funded by the WRC. The assessment indices include habitat, water quality, vegetation, macroinvertebrates, fish and geomorphology. The Geomorphological Driver Assessment Index (GAI) was developed by Rowntree in collaboration with Du Plessis and Rountree (Rowntree 2013*). Scoring of assessment indices is done relative to a reference condition – that which existed prior to human impact – and research into the reference condition for geomorphology was undertaken by Du Preez and Rowntree (2006*). Whilst the zonation system of Rowntree and Wadeson (1999*) gives an approximate prediction of channel morphology, Du Preez and Rowntree (2006*) stressed the dynamic nature of river geomorphology and cautioned against being able to define a stable pre-development channel morphology.

Geomorphologists also contributed to the WRC project on the application of DRIFT to semi-arid rivers (Seaman et al. 2013*). Because of the importance of pools as refuge habitats during prolonged dry seasons, the emphasis shifted from securing adequate flows over riffle habitat, to maintaining the pool habitat of sand-bed rivers in a flow regime where extreme flood events were especially important. DRIFT requires specialists to produce indicator response curves that can be used to model dynamic changes to an indicator (e.g. channel width, sand grade). This presented a new challenge to the geomorphologists on the team who had to use expert knowledge to draw up these relationships.

Conclusion

The WRC has had a major impact on geomorphological research in South Africa. We now have a far better understanding of different river processes and their roles in determining the structure and functioning of river ecosystems. WRC-funded projects have not only increased our understanding of river form and process but have also raised the profile of fluvial geomorphology among ecologists, engineers and water resource managers. Geomorphological research during the KNPRR Programme, for example, attracted international scientists and raised the profile of geomorphology as a key ecosystem component. As a result, geomorphologists have been invited to make a significant contribution to water resource management in South Africa. WRC- funded projects have also provided the opportunity for training post graduate students who have gained higher degrees, often while being part of an interdisciplinary team.

Unfortunately, however, WRC-funded projects have not left a legacy of active fluvial geomorphologists, and their numbers remain low. There is an urgent need for a new cohort of fluvial geomorphologists with the relevant experience, to advance the science in South Africa. Another concern for the future is the lack of climate change research. Climate change will certainly have significant geomorphic responses, with consequences for the management of aquatic ecosystems. There has, however, been no WRC funded research on this topic to date.

INSTREAM FLOW REQUIREMENTS (IFRS)

The National Water Act requires that all significant water resources be classified and that the Reserve be determined (Rowlston 2011*). The Reserve, also known as environmental (or instream) flows, represents the amount of water left in, or released into, a river system with the specific purpose of managing some aspect of its condition. The setting of environmental flows (IFRs) in South Africa started with a multidisciplinary workshop at Skukuza in March 1987 to determine flow requirements for Kruger National Park Rivers (Bruwer 1991*). From these humble beginnings numerous systems were developed to assess Environmental Flow Requirements. The research field of Environmental Water Requirements (also known as Instream Flow Requirements and Ecological Reserve) focuses on the management of water resources from an environmentally sustainability perspective. The WRC has played an important role in the management, dissemination, and implementation of research in the field of Environmental Water Requirements (hereafter referred to as EWR) in South Africa. (Winter et al. 2009*).

A note on terminology

The literature on water allocations for the environment contains a number of terms, usually presented as acronyms, for essentially the same thing.

- "The Reserve" is a term derived from the South African National Water Act and refers to the amount of water to be reserved for basic human needs and for sustainable maintenance of aquatic ecosystems (which are often called "the resource")
- IFRs (Instream Flow Requirements), sometimes used interchangeably with EFlows; refers to the amount of water ("flow") required to maintain a river in a particular state
- EFlows (Environmental Flows), a more recently coined term; refers to the amount, timing and quality of water (flow), sediment transport and the movement of biota required to sustain a river in a particular state
- RDM (Reserve Determination Methodology) refers to the methods used by DWS to assess the IFR (Note: the acronym RDM (Resource Directed Measures) can also apply when used in the context of the National Water Act and DWS).
- EWRs are environmental water requirements; although the term applies to all freshwater ecosystems, it is often used with reference to wetlands, where flow is usually irrelevant
- EWAs are environmental water allocations: the amount of water allocated to an aquatic ecosystem by one of the methods defined above

Contributions by the WRC to IFRs

The Building Block Methodology (BBM), one of the world's first holistic EFR approaches, was developed by a group of South African river scientists in water resource developments with funding and support from the National Department of Water Affairs and Forestry (DWAF) and the WRC (King and Tharme 1994*; Tharme and King 1998*; King et al. 2000*; King and Pienaar 2010*). The BBM has since been followed by two more EFR methods. The Downstream Response to Imposed Flow Transformations (DRIFT) was developed with WRC funding (Brown and King 1999; King et al. 2004*; Brown et al. 2005*; Brown et al. 2013), whereas the Habitat Flow Stressor Response (HFSR) method was mostly developed without WRC funding (O'Keeffe et al. 2002; IWR Source-to-Sea 2004), although project K5/1160 of the WRC further contributed to the development of the HFSR approach to EFR assessment (Hughes 2005*). Both DRIFT and the HFSR methods are designed to produce multiple scenarios and have been applied in EFR studies in Southern Africa, especially South Africa and Lesotho (King et al 2004*; Brown et al 2005*; Brown et al 2013*). The BBM, DRIFT and HFSR were developed for use in perennial systems, but South Africa still needed a method for EFR assessments in non-perennial systems. Research into the development of a non-perennial EFR method started in 2005 using the Seekoei River as a case study (Rossouw et al. 2005*; Seaman et al. 2010*). A prototype EFR method for non-perennial rivers (Arid-Proto) based on DRIFT was developed and applied in the Seekoei River. Arid-Proto was subsequently improved and adapted. This revised method named DRIFT-ARID was subsequently developed using the Mokolo River as a case study (Seaman et al. 2013*).

Hydraulic analyses are essential for providing the critical link between hydrology and other factors necessary to set the EFR (Jordanova et al. 2004*). Hydraulic modelling provides the link between aquatic habitats and stream flow. Research in the modelling of cross-sectional velocity distribution for a given discharge is required in order to recommend ecological flows for fish and macroinvertebrates (Hughes 2000), as was done, for example, by Paxton and King (2009*) to determine the spawning and recruitment requirements for threatened fish species. There was also a need to develop a continuum of methods from the high confidence, detailed approaches to the low confidence, low-cost simple approaches required by the Department of Water and Sanitation. These needs resulted in the development of the Desktop and Rapid estimation procedures (Hughes and Münster 2000*) as well as SPATSIM (Spatial and Time Series Information Modelling) developed at the Institute for Water Research (IWR) at Rhodes University with partial funding from the WRC (Hughes 2005*). The Desktop Reserve model was used extensively for rapidly generating Reserve information (Hughes 2005*). A new version of the Desktop Reserve model was subsequently developed to include more explicitly the links and relationships between hydrology, hydraulics, and ecological responses (Hughes et al. 2008*; Hughes et al 2011*).

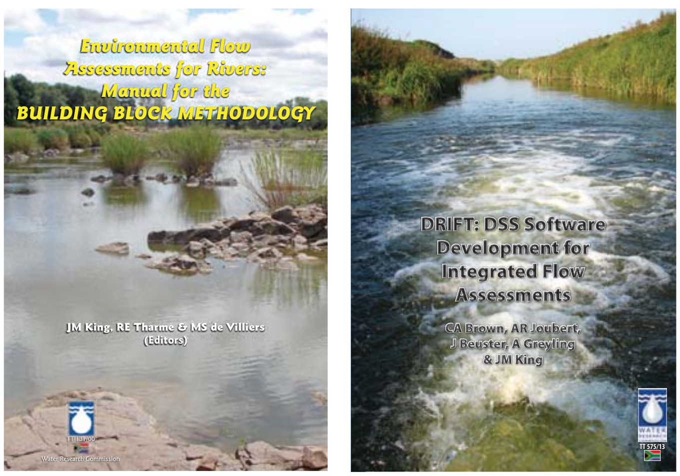


Figure 7. BBM was the first locally-developed EFR method in South Africa, and was later followed by DRIFT.

The Water Resource Classification System (WRCS), which is identified as a "set of guidelines and procedures for determining different Management Classes" (Brown and Louw 2011*) was developed to allow the classification of water resources (Dollar et al. 2010, IWR Source-to-Sea 2004).

Figure 8. DWS staff conducting a hydraulic survey in the upper Matlabas River for a rapid EWR study in the Marakela National Park Limpopo. (Credit: Christa Thirion)

Figure 9. Pumza Dubula (DWS) and André Hoffmann (MTPA) collecting fish by seine netting. (Credit: Christa Thirion)

Capacity development

The implementation of Ecological Water Requirements (EWR) in Integrated Water Resource Management (IWRM) was hampered by the lack of human capacity in the field, and by the lack of methods for assessing the Reserve and for integrating the results within existing water resource management strategies. Twenty years of EWR curriculum development culminated in the launch of a Master's Programme in Environmental Management with specialisation in EWR in 2016 at the North West University (Wepener 2016*). Despite this curriculum being available, there has been a lack of formal capacity building and training within the EWR field. The WRC thus funded a project to increase training and skills development of human resources within the water resources management sector and to evaluate an integration framework within EWR and its implementation (Malherbe et al. 2019*).

THE RIPARIAN ZONE AND ITS ASSOCIATED VEGETATION

Riparian areas "are transitional semi-terrestrial areas regularly influenced by freshwater, normally extending from the edges of water bodies to the edges of upland communities" (Naiman et al. 2005 (1)). They are found adjacent to dams, rivers and wetlands and have plant communities uniquely adapted to seasonal changes in water availability in perennial rivers, and inter-annual changes in water availability in non-perennial rivers. Riparian plants grow along a gradient of changing conditions from wet, in the water and at the water's edge, to dry laterally and higher up the banks. The plants growing there are influenced by floods (surface water): smaller intra-annual floods provide wetting through the year and larger floods carry more force and reach higher up the bank, removing encroaching terrestrial plants not able to withstand their scouring force. The plants are also influenced by the availability of groundwater. Many trees, in particular, access groundwater throughout the year via deep root systems. Groundwater also sustains riparian trees that grow on non-perennial rivers.

Here we deal only with WRC-funded work on rivers, wetlands being dealt with in Chapter 9. Thirty-two WRC-funded reports are available on riparian plant research, spanning the years 1998 to 2019. These reports cover four categories: water use, environmental flow requirements for rivers (EFlows), river rehabilitation, and management.

Figure 10. Marginal and aquatic plants on the Elandspad River. (Credit: Karl Reinecke)

Water use

Earlier work focused on the use of groundwater by vegetation (Scott and Le Maitre 1998*) and laid out research priorities for South Africa, some of which were picked up by later projects, for example a study on the effect of alien plants on surface water resources (Le Maitre et al. 1998*) and on dam yields (Le Maitre and Görgens 2003*). Colvin et al. (2009*) looked at the ecological effects of large-scale groundwater development of the Table Mountain Group (TMG) Aquifer and initiated a long-term monitoring programme. This programme still collects monitoring data on groundwater-dependent rivers and seeps (and their biotas) that may be affected by abstraction in the future. Despite work on water-use by indigenous riparian plants in the Kruger National Park (Everson et al. 2001*), most of the earlier research projects were based on the assumption that indigenous plants use less water than exotics. This hypothesis was really only tested empirically in later research projects that sought to close this gap (Gush et al. 2015*; Starke et al. 2016*; Scott-Shaw et al. 2016*), with mixed results.

The earlier work had a big impact at the time because it provided evidence to support the initiation of the Working for Water programme (www.environment.gov.

za/projectsprogrammes/wfw). This was a public works programme, designed to improve water resource conservation and alleviate poverty, that still employs and trains local residents to clear exotic plants from river basins nationwide. This project has had both positive and negative effects. Clearing vast tracts of aliens in wilderness areas, and providing employment, have been hugely beneficial. On the other hand, clearing efforts have not always been sustainable, for instance in cases where funding priorities changed. In other cases follow-up treatments have not been sustained resulting in money wasted as newly cleared areas are re-invaded. A study by van Wilgen et al. (2012) assessed the effectiveness of the national-scale invasive alien plant control strategy in South Africa.

Environmental flows (EFlows)

A detailed description of the development of EFlows may be found elsewhere in this chapter. Only the components of Eflows directly related to riparian vegetation are included here.

The seminal work on EFlows that began as part of the Kruger National Park Rivers Research Programme (Breen et al. 2000*) included work on large floodplain systems, and involved collaboration with international scientists (Botha 2001*). The Building Block Methodology (BBM: King et al. 2000*; 2008) that was developed from this work included a manual that described the tasks required to assess EFlows for riparian plants (and other components of the biota) on perennial rivers. The BBM, and later the holistic scenario-based DRIFT method (King et al. 2004*; Brown et al. 2005*) both relied upon expert judgement to predict how much water riparian plants of perennial rivers need at different times of the year to sustain growth and reproduction. Further work on ecohydraulics, making links between riverine ecosystems and flow, including riparian vegetation, was consolidated by James and King (2010*). Some of the assumptions for riparian plants were tested empirically and found to be true (Reinecke and Brown 2013*), which bolstered confidence in the results of EFlows assessments as riparian plants are important for the stability of rivers and critical as habitat for other organisms. For example, the 1:2 year floodline separates the wet riparian bank, where obligate riparian plants grow, from the dry riparian bank where mixtures of riparian and terrestrial plants grow. It was also shown that plants growing in the riparian zone closer to the water's edge release their seeds at low flow, which results in their preferential dispersal to the lower parts of the river bank. Conversely, plants that occur higher up the bank release their seeds during high flow, resulting in their dispersal higher up the river bank.

People started thinking about EFlows for non-perennial rivers at about the same time as BBM and DRIFT were conceived (Roussouw et al. 2005*). This required new ways of thinking because the habitats along non-perennial rivers are connected when flooded and disconnected when dry; with plants having to rely on groundwater to a large extent. The DRIFT-ARID method was developed by Seaman et al. (2013*) but has not since evolved because the topic was found to be more difficult than anticipated.

The EFlows work done for perennial rivers from BBM that culminated in DRIFT went on to be used internationally to assess EFlows for rivers around the world. This has had a significant impact on the way rivers are managed in many countries as more scientists make use of the method worldwide. The value of this work is evidenced by the fact that Jackie King was awarded the Stockholm Water Prize in 2019 for her work in this field.

Management

Several projects were designed to assist in the management of riparian areas. A method, called the Riparian Vegetation Index, was developed by Kemper (2001*) during the KNPRRP to assess the health or condition of riparian plants. This initiative was taken further by a joint WRC and Department of Water Affairs (DWA) project that developed a suite of methods for assessing river health. The one designed to assess the condition of riparian areas is called VEGRAI (Vegetation Response and Assessment Index: Kleynhans et al. 2007*). This method is widely used in EFlow assessments around the world but is also one of the important components of the River Ecostatus Monitoring Programme (www.dws.gov.za/iwqs/rhp/publications.aspx) that DWS operates nationally, along with complementary methods for fish, water quality, geomorphology and aquatic invertebrates. Other work has gone into defining buffer zones (Macfarlane 2017*; Macfarlane and Bredin 2017*) to protect the integrity of riparian and in-channel habitats. Many of these were developed in response to the growing needs of the DWA. Two other projects dealt with basin-wide issues that affect riparian plants and ways in which riparian plants can be included in wise and integrated management of catchments (Everson et al. 2007*), and in particular to incorporate local livelihoods and stakeholders in their management (Jaganyi et al 2008*).

RESERVOIRS

A reservoir refers to the body of water impounded by a dam. There are currently over 5 000 dams in South Africa that are registered as dams with a 'Safety Risk'. The safety risk of a dam is based on wall height and hazard potential with respect to potential loss of life, or negative impacts on the economy or the environment. There are currently 1 540 dams in South Africa that are classified as 'Large Dams' as defined by the International Commission on Large Dams. Large dams collectively store about 64% of the mean annual runoff from rivers in South Africa and have led to unprecedented socio-economic benefits associated mainly with improved assurance of water supply.

Driekoppies Dam, on the Lomati River, for example, was completed in 1997 and provides irrigation water to over 12 000 hectares and drinking water to over 180 000 people in the Nkomazi Region (Figure 11).

Figure 11. Driekoppies Dam, Lomati River, completed in 1997. (Credit: Rob Palmer)

The most suitable sites for dams in South Africa were developed mostly in the 1970s, when the Orange River and Thukela-Vaal Projects were completed. Since then, the rate of dam construction has slowed, mainly because suitable sites for dams are limited (Figure 12). Providing water becomes increasingly difficult as water demands increase and the costs per unit of reservoir yield also increase.

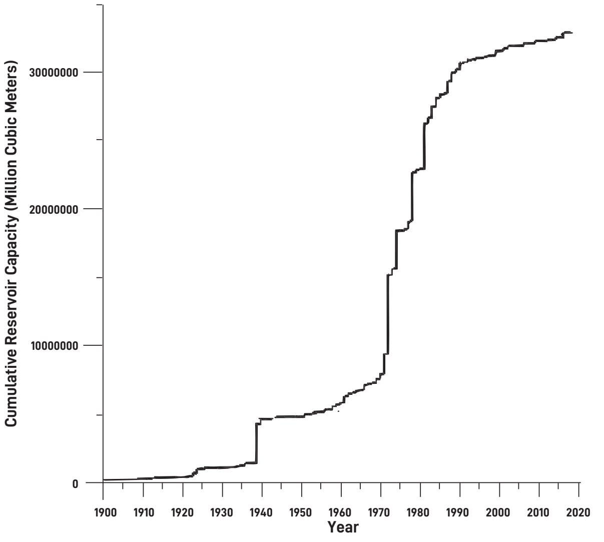


Figure 12. Cumulative capacity of reservoirs in South Africa since 1900. Source: Dam Safety Office - List of Registered Dams May 2018.

Large dams in South Africa have inundated a combined area of about 4 000 km^2, which is more than double that of the City of Ekurhuleni Metropolitan Municipality (on the East Rand). It is inevitable that the inundation of such a large area carries several unintended consequences. Since its inception in 1971, the WRC has funded many research projects aimed at understanding the complex trade-offs and unintended consequences of reservoirs. These include studies on eutrophication, sedimentation and dam safety, inter alia.

Eutrophication

One of the unintended consequences of reservoirs is the excessive accumulation of plant nutrients, a process known as eutrophication (Figure 13). Reservoirs in South Africa, in summer, are typically warm on top and cold on the bottom, but in winter the upper and lower layers of water mix and temperatures become uniform from top to bottom. Mixing typically occurs towards the end of summer and the process often leads to a spike in the availability of nutrients, which constitutes one of the main causes of eutrophication in reservoirs in South Africa. Eutrophication has many negative consequences, including taste and odour problems; increased costs of water treatment; increased risks of mass mortality of fish and livestock; reduced property prices; increased risk of water-borne diseases; and reduced biodiversity. The WRC has produced over 80 research studies on eutrophication in South Africa (Frost and Sullivan 2010*).

One of the first of such studies involved the collection of detailed data on the hydrological, physical, chemical and biological properties of 21 large reservoirs every two weeks for one year (Walmsley and Butty 1980). The study found that one of the key causes of eutrophication is orthophosphate loading, and this finding led to the Department of Water Affairs and Forestry in 1985 introducing a water quality standard for effluent discharges of 1mg/ℓ orthophosphate in sensitive catchments (Grobler and Silberbauer 1984*). The WRC then funded various research projects evaluating the impact of the discharge standard (Grobler and Silberbauer 1984*; Chutter 1989*; Chutter and Rossouw 1992*). These studies confirmed the importance of orthophosphate in driving eutrophication and highlighted the need for improved implementation of the standard. A subsequent study found, however, that the standard alone was inadequate to manage eutrophication and that additional interventions were needed (Harding 2015*). Additional interventions included the development of dam operating rules that minimise thermal stratification (Bath et al. 1997*), and an internet-based Nutrient Enrichment Assessment Protocol (Rossouw et al. 2008*). These and other interventions have not solved the problem of eutrophication entirely but, where they have been applied, they have helped to reduce its negative consequences.

Figure 13. Eutrophication visible in Rietvlei Dam, Tshwane. (Credit: Lani van Vuuren)

Sedimentation

Another unintended consequence of reservoirs worldwide is the trapping of sediments. For example, Mapochs Dam on the Masala River, was completed in 1969 and by 2012 the reservoir had lost almost all storage capacity because of sedimentation (Figure 14). Sediment trapping reduces reservoir storage capacity and increases the risks of erosion downstream of the reservoir (Beck and Basson 2003*). The WRC has funded several key projects investigating sedimentation in South African reservoirs. One such study estimated that the trapping of sediments caused an annual loss of storage capacity in South African reservoirs of about 130 million m^3 (Basson et al. 2003*). Another study detailed the sediment yield patterns in southern Africa and thereby developed a new sediment yield map for the subcontinent (Rooseboom 1992*). Strategies for mitigating the trapping of sediments in reservoirs are limited but include dredging and density-current venting (Basson et al. 2003*). A study on dredging found that the costs of dredging are generally higher than the costs of creating additional storage, but that dredging may be considered on occasion, especially in arid or semi-arid regions (Basson and Rooseboom 1999*).

Density-current venting is a technique in which river sediment loads are transported through a reservoir and released to the downstream river through bottom outlets (Basson et al. 2003*). The technique relies on the availability of sufficient fine sediment with suitable boundary conditions and turbulent inflow (Basson et al. 2003*). The technique was applied to the design of Mohale Dam in Lesotho, as well as when evaluating the location of the Mohale-Katse intake (Basson et al. 2003*). Other recommendations that minimise the downstream consequences of sediment trapping include the design of new dams with multiple-level outlets (Beck and Basson 2003*). In addition, dam outlets should be designed with sufficient capacity to release managed floods that maintain pre-dam downstream geomorphological processes as far as possible (Beck and Basson 2003*). The Berg River Dam, completed in 2007, was the first dam in South Africa designed to release high flows of up to 200 m^3/s (Van Vuuren 2012). The first Integrated Sediment Management Framework for South Africa was developed in 2013, with funding from the WRC (Jeleni et al. 2013*).

Figure 14. Mapochs Dam, on the Masala River, showing accumulation of sediments. (Credit: Rob Palmer)

Dam safety

Dams are not designed to fail. However, the evidence indicates that dams do fail on occasion, and the WRC has therefore funded several key projects that have investigated issues related to dam safety. These studies include foundations for concrete dams (Geertsema 2000*), flood capacity for dams (Cullis et al. 2007*; Görgens et al. 2007*), and the development of guidelines for the determination of freeboard for dams (Bosman and Basson 2011*; Bosman et al. 2011*). The guidelines on freeboard for dams were reviewed and adopted by the South African National Committee on Large Dams (SANCOLD). Information collected during these and related WRC-funded research projects was used to update the National Dam Safety Regulations, in 2012. The new regulations ensure alignment with the National Water Act of 1998 and, as such, place more emphasis on the social and environmental impacts of dams than did the previous regulations, published in 1986.

Conclusions

Scientific information collated by WRC-funded projects has been made readily available and has been used to improve the design, construction, operation and monitoring of reservoirs in South Africa, as well as in southern Africa and possibly globally. A review of reservoirs and their management by Hart and Hart (2006*) highlights a widening gap between scientific knowledge and management of water resources in South Africa, however. The widening gap is attributed to various factors including: 1) deficiencies in scientific expertise caused partly by an aging cohort of water resource experts; 2) a narrowing window of opportunity for transferring skills to a younger generation; 3) disjointed information and databases on water resources; 4) disorganisation resulting from increased numbers of agencies responsible for water resource monitoring and management, from local dam owners, irrigation boards and water management authorities to various provincial and national departments; and 5) limited primary data collection after 1990.

An implication of these findings is that the WRC is likely to play an increasingly important role in improving scientifically-based decision-making which is greatly needed to protect and manage one of South Africa's most precious resources, namely, freshwater. Furthermore, the limited availability of suitable sites for dams highlights the importance of managing and maintaining the existing reservoirs that are needed to provide water security.

URBAN RIVERS

The sustainable management of urban rivers represents a particular challenge, as most of their catchment areas have usually been highly modified and, in many instances, natural watercourses are indistinguishable from artificial stormwater systems. Even lined systems still connect to remnant, more natural rivers or wetlands and /or ultimately to the sea, however, and unlined channels through urban areas sometimes provide the only continuous ecological corridors through otherwise ecologically sterile areas. In South Africa, many urban rivers are characterised by high loads of litter and pollutants, with the latter often deriving from large populations living in unserviced or poorly serviced informal settlements, or in unserviced backyard dwellings within formal developments.

Figure 15. Even fairly degraded urban rivers such as the Liesbeek River in Cape Town still provide green corridors through ecologically sterile urban areas and can be important recreational areas. (Credit: Liz Day)

The WRC's contribution to urban river research

While little WRC-funded research has focused on urban river ecology, there has been considerable research relating to the amelioration of stormwater quality and quantity, which play important roles in determining urban river condition. Since urban rivers form a significant part of the stormwater system, such research and its application in urban areas is pivotal to their management and condition.

Figure 16. Opportunities to improve habitat quality in urban rivers can be limited by development encroachment, water quality and canalisation. (Credit: Liz Day)

Pollution abatement

In its earliest phases, the most relevant WRC research in this regard was directed towards improving technologies for the reclamation of treated effluent for re-use, rather than disposal via increasingly polluted watercourses (e.g. Funke 1975; Cillie et al. 1979; Smith and Wieches 1981). Development of this kind of technology had an indirect impact in both highlighting and triggering increasing efforts to address watercourse pollution and the knock-on environmental impacts of large-scale eutrophication.

By 1974, the need for research to address 'stormwater and surface pollution' was formally included in the WRC's National Master Research Plan and National Priority Research Programme (WRC 1974), with the focus remaining for some time on effluent and other waste treatment, rather than on rivers themselves as part of the stormwater system. By 1997 there was, however, a growing recognition of the impact of ineffective solid-waste disposal on pollution loads in rivers and impoundments in urban areas, and the threat of steadily increasing communities living in informal settlements with little or no solid-waste-disposal services (Campbell 2001*;

Wood et al. 2001*). Project reports that looked at solid-waste services, and methods to collect litter both at source and in receiving aquatic environments such as rivers, included those of the Palmer Development Group (1996*) and Armitage et al. (1998*). At about the same time, new concepts such as integrated catchment management were introduced into the WRC lexicon, looking at research into the efficacy of various catchment-management techniques to ensure a reduction in urban litter reaching drainage systems, and relationships between communities and their catchments (e.g. Armitage and Rooseboom 2000a; 2000b; and 2000c; Grobicki et al. 2001*; Marais and Armitage 2003*).

Integrated urban water management

In the late 1990s to 2000s there was a growing recognition of the interconnected nature of urban catchments, which required interventions that cut across all aspects of sanitation, waste disposal, urban stormwater and runoff, water reticulation, and human attitudes and activities. This was reflected in the inclusion by the WRC of a new field of research, namely Integrated Urban Water Management (IUWM) (see WRC 2001). Early projects in this field included general guidelines for the management of urban runoff water quality (Coleman 2001*; Ashton and Bhagwan 2001*) focusing on dense, poorly serviced settlements. Other projects were funded that aimed to identify, characterise, prioritize and in some cases provide broad management guidelines for urban stormwater management issues requiring attention in South Africa within the context of human settlements (e.g. Murphy 2006*; Stephenson et al. 2006*; Carden et al. 2007*; Henning et al. 2007*; Burke and Mayer 2009*).

A shift towards holistic management solutions

Stormwater planning and design at this time still focused on collecting runoff and channeling it to the closest watercourse, frequently having a significant impact on the environment through the resulting erosion and siltation. By 2008, however, WRC-solicited projects showed a shift in attention towards alternative stormwater-management technologies. These projects for the first time considered the (then relatively new) principles of water-sensitive urban design systems (WSUDS), which aimed to deal with stormwater as close to its source as possible. Major research outputs included Armitage et al (2013*), which included, inter alia, reviews of international WSUDS practices, South African case studies and WSUDS Guidelines. Importantly, local municipalities (e.g. City of Cape Town, eThekwini Municipality, Johannesburg Municipality, City of Tshwane) were also included in research teams and project reference groups, which meant that knowledge dissemination pathways between research teams and those implementing new concepts on the ground were more effective than if the practitioners had been excluded from the teams. This is evidenced in the City of Cape Town's inclusion of WSUDS concepts in its 2009 stormwater management policy for new developments (City of Cape Town 2009). The notion of water-sensitive cities started to be explored in this context, and city-scale projects included Seyler et al (2016*) and Fourie et al (2020*).

At the same time, the enormous problem of settlements living without access to sanitation was a different focus for projects that recognised both the effects on human health and welfare and the downstream pollution associated with such situations. Useful research attempting to quantify these issues, understand their root causes and provide innovative ways of addressing them continue to date, including Winter et al (2011*) and Morgan (2017*). Chapters 4 and 12 deal in more detail with some of these aspects.

Around 2014, the notion of the Green Economy started to be seen in WRC projects, and although not necessarily directly related to rivers, they indicated a shift in attitude in town planning and development, which could potentially reflect in reduced urban impacts to rivers over time, at least in association with new, serviced developments. Research reports emanating from this period include Amis and Solomon (2016*), while the 2017-2019 drought in the Western Cape probably stimulated research efforts into the impacts of increasing domestic greywater re-use, promoting the findings of guidelines around the applicability of this practice (e.g. Carden et al. 2018*).

The significant body of research funded by the WRC on urban runoff and its management, while mostly relating to engineering practice and identification, characterisation and measures to address pollution at source, has significant implications for urban rivers. This is because these systems are the receiving bodies of catchment-scale activities and are increasingly affected by poorly serviced communities in their catchments. Research on urban runoff preceded a focus on more active rehabilitation measures within the rivers themselves, but certainly highlighted the extent of problems afflicting urban rivers. Thus, after an initial focus on pollution abatement, WRC projects moved steadily towards embracing more holistic and greener approaches to river management, which increasingly included consideration of active river rehabilitation measures. These are discussed in the following section.

Figure 17. Wet detention pond with forebay at this shopping centre parking area allows stormwater attenuation and water quality purification. (Credit: Liz Day)

Future research requirements

Unfortunately, despite the research generated with regard to urban runoff, the condition of urban rivers appears to have deteriorated significantly in many areas (e.g. Thirion and Jafta 2019; E Day et al. 2020), largely as a result of uncontrolled pollution and the passage of waste into these systems.

Identifying and applying practical approaches to reducing burgeoning pollution are important areas for ongoing research. At the same time, research that demonstrates the value of urban rivers for both local communities and as ecological corridors through urban areas is lacking, although such research could provide impetus to improve conservation efforts to address these issues. Research into the identification of nodes of more natural ecological function, and measures to support these, could ensure that the rate of ecological impacts is slowed. At the same time, research that critically evaluates the efficacy of actual implementation of stormwater management systems and green infrastructure in South African cities should be undertaken on an ongoing basis, so that adaptation to local conditions can take place.

RIVER REHABILITATION

Driver et al. (2004) found that rivers in South Africa were generally in a worse condition than terrestrial systems, with more than 80% considered to be threatened at the time of that report. By 2018, Thirion and Jafta's (2019) State of Rivers report for the 2017/18 hydrological year showed that the situation was no better, with a mere 16% of the sites monitored nationally being in a Present Ecological State of B or better, and most of these less-threatened sites lying in the upper reaches of rivers. The report noted that riparian zones and instream habitats had all deteriorated because of land-use activities, with rivers in densely populated areas generally being in poor condition due to the lack of proper management and maintenance of wastewater treatment works, and insufficient capacities of these works for the populations served.

Against this background, and given the scarcity of water resources in South Africa, river rehabilitation measures are increasingly important. Rehabilitation can be defined as promoting the recovery of ecosystem functions and values in a degraded system, in order to regain some of the value the system previously had to society (Dunster and Dunster 1996; Grenfell et al. 2007).

The WRC's contribution to river rehabilitation research

Any research that contributes to our understanding of river function and diversity (e.g. the Kruger National Park Rivers Research Programme, funded by WRC in the 1980s to early 2000s) is useful in guiding river rehabilitation interventions. From this perspective, it can be argued that the WRC has, since its inception, contributed to research that assists directly or indirectly in the rehabilitation of South Africa's river systems. This section, however, focuses on those projects that were specifically funded to address and/or inform river rehabilitation activities, while the more general river ecology, hydrology, hydraulics and biodiversity-focused projects are highlighted elsewhere in this chapter.

In the first years following the WRC's formation, river rehabilitation was addressed indirectly through projects primarily targeting water quality issues, particularly in runoff from urban areas (see urban rivers section). Although the WRC's 1974 National Master Research Plan and National Priority Research Programme (WRC 1974) included catchment conservation and management among its themes, with the need for research on the "Effect of erosion and damage to sponges and catchments", no specific river-rehabilitation-focused projects were included at that time. It was not until 1997 that the first directly rehabilitation-focused research project was funded, prompted by the commencement of the National Government's Working for Water Programme, which aimed at creating job opportunities and freeing up water at a catchment scale through the clearing of invasive alien vegetation. This early research (see Versveld et al. 1998*) provided initial quantification of the impact of woody alien invasion on water resources, which was followed by several other projects focused on alien clearing decision-making and effects (Le Maitre et al. 2000; Le Maitre and Görgens 2003*).

A focus on river rehabilitation

The above projects had catchment- rather than river-scale focuses. The first overtly river-focused rehabilitation project funded by the WRC was precipitated by an acknowledgement of the lack of experience and guidelines for effective riparian rehabilitation, and provided both a basic decision-support system for riparian rehabilitation as well as pilot riparian rehabilitation project outcomes (Quinn 2003*). Research into 'Adaptive Management' was also pursued, particularly through the KNPRRP, and this included the identification of measures to prevent ongoing riverine degradation (Breen et al. 2002*).

As management and decision support systems started being produced, they led to more focused rehabilitation tools and guides. These included a global literature review and research on the ecological (King et al. 2003*) and geomorphological (Wadeson and Rowntree 2005*) principles for river rehabilitation. Meanwhile, van Zyl et al. (2004*) provided early insights into the economics of rehabilitation, with cost/ benefit analyses considering inter alia the effect of river and wetland rehabilitation (versus degradation) on property values.

In 2002, the WRC introduced Key Strategic Area (KSA) 2, which included an Ecosystem Protection Thrust, aimed in part at addressing issues such as management of the side-effects of engineering structures, of the introduction of alien biota and of the rehabilitation of abused ecosystems. At the same time, it was evident that some other countries in the world were advancing in their river rehabilitation strategies and expertise, whereas rehabilitation as a field of practice in South Africa was still in its infancy. Funds were granted for research into Australian procedures for river rehabilitation, as well as their trialing and adaptation to South African rivers. The research outputs provided valuable guidelines for local urban river rehabilitation (Uys 2003*, Uys 2004a* and 2004b*).

A growing realisation of the dire threats facing many of South Africa's indigenous freshwater fish (e.g. Cambray 2003) led to WRC-funded research into rehabilitation measures to address some of the issues affecting indigenous fish populations. These included projects targeting fish species affected by instream structures such as weirs and alien fish invasion. Research projects provided valuable input into the effects of instream barriers on faunal migration and the development of criteria for the design of fish ladders (Heath et al. 2005*; Bok et al. 2007*; Wasserman et al. 2011).

A large proportion of the direct river rehabilitation research funded by the WRC in the period 2003-2013 revolved around the rehabilitation of alien-invaded riparian zones. This resulted in an increased understanding of the community structure and functioning of vegetation in riparian areas, as well as the identification of the effects of alien plant invasion in these zones and best-practice recommendations for their removal and the re-establishment of indigenous vegetation (e.g. Reinecke et al. 2007*). Other projects explored the benefits of river rehabilitation on rural employment through payment for environmental services (Fourie et al. 2013*).

Figure 18. Gabion weirs and indigenous planting effectively address severe channel incision and erosion in this suburban Cape Town stream. (Credit: Liz Day)

Figure 19. Alien clearing along the Berg River to allow replanting with indigenous vegetation and the re-establishment of riparian fringes. (Credit: Liz Day)

National legislation

Ironically, a significant impediment to river rehabilitation is national legislation, compliance with which requires often costly and time-consuming authorisation processes for the implementation of river rehabilitation measures (for instance, bank reshaping that involves the disturbance or removal of more than $10m^3$ of soil from a site currently requires authorisation in terms of the National Environmental Management Act (NEMA) (Act 107 of 1998) (Rountree et al. 2016*). Braid (2014*) assessed the legal landscape and outlined tools to assist both landowners and regulators to set clear, feasible and practical objectives for rehabilitation, focusing primarily on urban watercourses.

Management guidelines

In 2013, the WRC funded the development of a comprehensive manual for the rehabilitation of rivers in South Africa. This resulted in a series of three manuals that included broad guidelines for drivers of river degradation and principles of river rehabilitation (Rountree et al. 2016*); a technical manual to address specific aspects of river rehabilitation, from alien invasion, through channel and bed erosion, to sediment removal as well as general river rehabilitation techniques and approaches at the scale of implementation (E. Day et al. 2016*); and a set of critically evaluated case studies (King et al. 2016*).

The above overt funding of guidelines for river rehabilitation measures has been supported by research demonstrating the benefits of healthy ecological infrastructure, which can be utilized to secure water for the benefit of society and the green economy (Sutherland et al. 2019*) and research findings that highlight the expansion of new informal settlements and other land uses in riparian areas, emphasizing the need to include political and constitutional drivers in rehabilitation frameworks (Dube et al. 2017*).

Monitoring of river rehabilitation projects

More recently, funding has allowed for projects that quantify and monitor aspects of river rehabilitation implementation.

These include monitoring following the removal of riparian alien invasive plants, the spread of which continues to undermine conservation efforts and contribute to catchment degradation (Jacobs et al. 2013*; Everson 2016a* and 2016b*, Jacobs et al. 2017*). Additionally, WRC funding has allowed insight into the role of rotenone in the removal of alien fish species from river reaches to allow for the conservation of threatened indigenous fishes (e.g. Woodford et al. 2012*; Weyl et al. 2016*). This enabled comprehensive monitoring of the post-treatment recovery of native biota in the Rondegat for up to 5 years after the initial intervention (see Bellingan et al. 2019*), creating valuable lessons learned for future alien fish-removal intervention.

Monitoring the efficacy of river rehabilitation efforts is critically important, as it allows learning and the development of practice in this relatively new science. Ideally all new river rehabilitation projects should be subject to post-implementation scrutiny and analysis. The recent inclusion of South Africa in the African Chapter of the Society for Ecological Restoration (SER), facilitated by the WRC (see Ntshotsho and Yapi 2014*), was instrumental in bringing the 8th SER World Conference on Ecological Restoration to South Africa in 2019, and means that our country is linked to a global network of (inter alia) riverine ecologists, engineers, social scientists and other professionals engaged in river rehabilitation efforts.

Figure 20. Fourways: Rehabilitation of an incised urban tributary of the Jukskei River, Fourways Gardens, Gauteng. (Credit: Liz Day)

Figure 21. Berg River 'before (top) and after (below)': Rehabilitation of the Berg River following bed and bank erosion as a result of a poorly designed bridge. Rehabilitation is expensive - it is cheaper to avoid degradation in the first place. (Credit: Liz Day)

Future research requirements

What is required from a research perspective is ongoing critical evaluation of river rehabilitation outcomes, to ensure that project-specific learning is passed on to the broader implementing community. This is important, as it will address concerns raised by Ashton et al. (2012*) regarding the growing gap between researchers and implementation bodies. The ongoing collation of critically evaluated rehabilitation case studies would be a significant contribution towards growing rehabilitation expertise. King et al. (2016*) made an initial contribution towards this process, but it should ideally be collated as a learning resource within the WRC website, thereby facilitating the inclusion of long-term monitoring of rehabilitation outcomes.

This leads to another area that would benefit from additional research, namely research into simulating (modelling) the long-term sustainability of river rehabilitation interventions in the absence of natural drivers such as fire, grazing, trampling by large mammals and natural flood regimes. Many river (and wetland) rehabilitation projects show early signs of success but later fail. This is as a result of the failure of rehabilitation guidelines to recognize the importance of disturbance in river ecosystem maintenance, and to emulate disturbance mechanisms successfully in rehabilitated systems – particularly in urban and agricultural scenarios, where ecological drivers have generally been uncoupled.

Further research into ways of ensuring the sustainability of river systems, particularly in managed environments such as agricultural and urban areas, would be useful in growing a practice of excellence. In addition, guidelines for river (and wetland) rehabilitation measures in specific landuse types and/or industries would be useful in promoting awareness and implementation in these sectors. Guidelines and follow-up implementation case-studies are required for rehabilitation efforts in catchments affected by polluted informal settlements, serviced urban settlements, agriculture, forestry, and areas affected by alien clearing.

SUMMARY

The WRC has contributed enormously to riverine research in South Africa since the late 1980s and has resulted in much seminal work that has been lauded internationally and is now used globally for river management. The emphasis of this research has been overwhelmingly management-oriented, although an important and positive consequence of this work has been a marked increase in our understanding of the ecology of South African rivers.

A number of common issues are noted by the authors of this chapter. In summary, they are as follows. The enormous work on EFlows and EWAs, led by DWS over the last twenty years or more, has allowed scientists in different disciplines to work together, thereby gaining an appreciation of each other's expertise, and developing a greatly increased understanding of river ecology. It has also provided the opportunity for training post graduate students who have gained higher degrees, often while being part of interdisciplinary teams.

On the other hand, authors note that the condition of South Africa's rivers has decreased during this same time period, despite the excellent work done and our increased management expertise. This is due at least in part to the widening gap between researchers (scientific knowledge) and the management of water resources, where management is often not based on sound scientific research. A major issue is the lack of adequate funding, both for the implementation of research outputs by mandated organisations and, just as importantly, for scientifically rigorous studies, particularly research in the ecological sciences, and critically, at postgraduate level. 'Fundamental science' studies are crucial for training enquiring minds, and these are virtually never funded by the WRC. This links with dwindling scientific expertise related to an aging cohort of water resource experts, and fewer mentors to transfer skills and insights to a younger generation. The WRC therefore needs to play an increasingly important role in providing funding for both fundamental ecological research and for educating young water professionals in the right skills to enable them to base their decision-making on scientific principles.

Research into the evaluation of ecosystem services that demonstrates the value of rivers, particularly those in urban settings, is lacking, as is a resource-economics approach to less obviously 'natural' systems, such as those that have been highly impacted by human activities. Both are required if our river systems and their ecosystem services are to properly valued, and therefore better conserved.

Monitoring the outcomes of WRC-funded management and interventions such as rehabilitation projects is critical, both to ensure that the intervention was appropriate and had the expected outcome, and also to allow project-specific learning to be passed on. The results of these monitoring projects and programmes should be collated and housed in an appropriate database, perhaps on the WRC website. Further research into how to ensure the rehabilitation and sustainability of river systems, particularly in managed environments such as agricultural and urban areas, would also be useful in growing a practice of excellence.

A more detailed analysis of the way forward may be found in the final chapter of this volume.



CHAPTER 09



1990 – 2020: THE WATER RESEARCH COMMISSION WADES INTO WETLAND RESEARCH

Kate Snaddon, Donovan Kotze, Lulu Pretorius and Faeeza Fortune

INTRODUCTION

Wetlands are complex and dynamic ecosystems, and their origins, biodiversity, ecological functioning, management, conservation and rehabilitation have been the subject of sustained interest and research for many decades. The relationships between humans and wetlands are also complex, inspiring researchers and managers to improve their understanding of the benefits that wetlands provide. The Water Research Commission (WRC) has been a key agent in the development, funding and implementation of wetland research initiatives and programmes, at a time when the pressures on wetlands are reaching unprecedented proportions. In the last two decades, wetlands have received priority through the work of visionary research managers who diverted significant resources towards these ecosystems (Phillips and Madlokazi, 2010*). To this extent, the WRC's Water Linked Ecosystem key strategic area received a Wetlands Award for Education and Skills Development in 2013.

A **wetland** is defined in the National Water Act (Act 36 of 1998) as "land that is transitional between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil." An **inland aquatic ecosystem** (i.e. a wetland or river) is described by Ollis et al. (2013) as an aquatic ecosystem with no existing connection to the ocean. These ecosystems are characterised by the complete absence of marine exchange and/or tidal influence.

Figure 1. A high-altitude wetland in the Lotheni area in the Drakensberg Mountains, KwaZulu-Natal. (Credit: Donovan Kotze).

A brief history of wetland research programmes in South Africa

Early research on inland water ecosystems in South Africa focused on reservoirs and water as a resource for human use (Walmsley, 1988; Ashton et al., 2012*). In the 1970s and 1980s, however, with an increase in water quality and ecological problems arising from unchecked utilisation of water resources, it was recognised that there was a need to undertake multidisciplinary research into the importance and functioning of the ecosystems and catchments that supply the resource. South Africa signed the Ramsar Convention at its inception in

1971 and brought it into effect in the country in 1975, ushering in a new and exciting era for wetlands and wetland research. The first two designated Ramsar sites in South Africa were De Hoop Vlei and Barberspan Bird Sanctuary (Malherbe et al., 2017*).

By the 1980s, the concept of a National Wetland Research Programme was put forward and implemented within the Inland Water Ecosystems Programme, led by the Council for Scientific and Industrial Research (CSIR). This initiative yielded some groundbreaking studies on human-wetland interactions (e.g. Heeg and Breen, 1982) but lost momentum in the early 1990s when a policy shift led to the abandonment of the programme (Phillips and Madlokazi, 2010*). However, wetland research continued across the country, through the CSIR's Foundation for Research Development (the forerunner of the current National Research Foundation), private sector programmes such as the Rennies Wetland Campaign and the Mondi Wetland Programme, and organisations such as the Worldwide Fund for Nature (WWF) and the Wildlife and Environment Society of South Africa (WESSA), contributing to the improved management and conservation of wetlands. Important wetland research in the 1990s was also coordinated by Geoff Cowan in the national Department of Environmental Affairs, culminating in the publication of a synthesis on South Africa's wetlands by Cowan (Cowan, 1995; Ashton et al., 2012*). At this time, a seminal series of WRC-funded research projects was overseen by Dr Charles Breen (then at the Institute of Natural Resources) to develop a wetland management decision support system (called 'Wetland-Use') for the KwaZulu-Natal Midlands (Kotze et al., 1994).

In 2000, the national Working for Wetlands Programme (WfW) was institutionalised under the auspices of the South African National Biodiversity Institute (SANBI), with the aim of promoting the protection, wise-use and rehabilitation of wetlands through co-operative governance and partnerships, with an emphasis on job creation and skills development (Dini, 2011). In 2003, the National Wetlands Research Programme (NWRP) was launched as a collaborative inter-agency initiative, to be administered by the WRC (WRC, 2002*; Malan and Day, 2005a*). The main thrusts of the NWRP were (1) Rehabilitation, (2) Wetland Health and Integrity, and (3) Wise Use. The Programme was responsible for the development of a number of tools and guidelines that are critical to good practice in the fields of wetland science, conservation, management, rehabilitation and utilisation. Spinoffs of the NWRP funded by the WRC include the Wetland Health and Importance Research Programme (WHI) and the Wetland Management Series of guideline documents. These tools and guidelines are described in more detail in this chapter.

More recently, the WRC supported the design of a National Wetland Monitoring Programme (NWMP) in collaboration with the Department of Water and Sanitation (DWS) (Wilkinson et al., 2016a* and 2016b*). The intentions of the NWMP are to minimise duplication of previous efforts, engage with a wide range of stakeholders, and provide sufficient information for DWS to implement the Programme (see the monitoring section for more on the NWMP).

Since 2007, the imperative to increase the understanding of wetlands in their socio-economic context has seen the WRC focus on applied rather than fundamental research (Phillips and Madlokazi, 2010). The role of wetlands as nature-based solutions to problems such as eutrophication, waste management, water treatment, and the mitigation of climate change has emerged over the past decade as a key research area (WRC Knowledge Review, 2008/9).

Wetland origins, hydrology and soils

The management, protection, rehabilitation and utilisation of wetlands requires an understanding of how wetlands form, how they are sustained, and how they function. Professor Fred Ellery and a group of co-authors made a considerable contribution to this understanding in their report, ***WET-Origins - Controls on the distribution and dynamics of wetlands in South Africa*** (Ellery et al., 2009*), part of the Wetland Management Series published by the WRC in 2009 (see the section on wetland rehabilitation in this chapter). In a report that brings together a couple of decades' of research, the authors underline the uniqueness of South African wetlands in comparison with similar ecosystems in northern temperate climates.

The African landscape is ancient, and southern Africa is situated at a much higher mean altitude than other continents, with the result that its rivers are in a long-term state of active incision. This, in combination with low rainfall and high evaporation, should reduce the occurrence of wetlands, which generally form through depositional processes. The South African landscape supports a vast number of wetlands, however, and a diversity of wetland types. WET-Origins describes the remarkable geological and geomorphological processes that underpin South Africa's wetlands, including: (1) the geology, geomorphology, climate and drainage of southern Africa; (2) wetland hydrology and hydraulics; and (3) wetland geomorphic controls and dynamics (Ellery et al., 2009*). It also provides a method for using the above descriptions to help develop insights into why a wetland occurs where it does and what implications this might have for the wetland's potential rehabilitation.

In other WRC-funded research, Grenfell et al. (2008) investigated the origin and geomorphic evolution of a floodplain wetland in KwaZulu-Natal, confirming previous findings that established that many floodplain wetlands in the eastern South African interior are formed upstream of resistant rock barriers across river courses. They described the dynamic relationships between mainstem rivers (or trunks) and their tributaries, which lead to a diversity of geomorphic features and hydrological regimes within floodplain wetlands, which provide potential habitat for a diversity of biota (see also Grenfell et al., 2009).

Wetland hydrology is recognised as one of the key drivers of wetland functioning. This subject was expanded upon in a WRC-funded project that aimed at understanding the hydrological processes important for wetlands within the context of the broader catchment, and to develop conceptual hydrological models for the hydrogeomorphic wetland types (see the section on wetland inventory, classification and mapping in this chapter) in South Africa (Maherry et al., 2016). The researchers developed simple water balance models for each wetland type, providing a useful hydrological framework for understanding how water moves into, through and out of wetlands.

In related work, Parsons and Vermeulen (2017) described the "hidden hydrology" of Groenvlei, in the Southern Cape. Parsons (2009) challenged the notion that the coastal wetland is sustained by discharge from the Table Mountain Group Aquifer, a semi-confined aquifer within the fractured formations of the TMG sandstones, which are the topographically dominant geological units in the south-western Cape. The 2017 study went on to scrutinise all available data and knowledge to conclude that its key hydrological drivers are direct precipitation and evapotranspiration, with groundwater playing an important but secondary role. Despite several WRC projects that have focused on understanding the occurrence and functioning of aquifer-dependent ecosystems (ADEs), the links between groundwater and wetlands remain unclear. Colvin et al. (2007) identified areas of South Africa that have a high probability of supporting ADEs, but stated that long-term, multidisciplinary studies are required to establish the occurrence of ADEs at a finer scale. This approach was applied at two sites in the Western Cape, and a number of wetlands were identified as being dependent on discharge from the TMG Aquifer (Colvin et al., 2009).

The Maputaland Coastal Plain (MCP) in KwaZulu-Natal is an area where the WRC has invested in specific studies on wetland distribution, diversity and functioning. The MCP is South Africa's largest sandy coastal aquifer (Kelbe and Germishuyse, 2010*), consisting of many different types of surface water bodies (such as rivers, floodplains, estuaries, swamps, pans, and coastal lakes), and containing 60% of South Africa's peat resources (Grundling et al., 1998). Sieben (2014*) states that the MCP "seems to be one of the richest areas of wetlands in the country, not only in terms of the various types, but also in terms of sheer extent". Currently, Maputaland is under severe pressure as a result of anthropological pressures, informal afforestation largely with pines and gums, and a cyclic drought period (Pretorius, 2019).

Figure 2. A handful of peat from the Maputaland wetlands. (Credit: Lulu Pretorius).

The WRC-funded studies in this area determined that wetland diversity is driven by the origin of the landscape setting (e.g. dune slack or floodplain), whether an area is a groundwater recharge or discharge area, and the source and dynamics of the water source (Grundling et al., 2014*). They found that groundwater is an important driver of wetland occurrence and distribution, and the principal source of water for its rivers, lakes and permanent wetland systems (Grundling et al., 2014*). As part of this study, the national peatland database and ecoregion model was refined and improved; and a protocol was developed for researchers to contribute data to the national peatland database (Grundling et al., 2017*).

In terms of vegetation diversity in the wetlands on the MCP, WRC-funded studies revealed that substrate type (specifically organic soil and clay percentage), soil parameters such as electrical conductivity and nutrient richness, and the hydrological regime had the largest influence over which wetland vegetation type dominated (Sieben et al. 2016; Pretorius et al. 2017). Plant species composition varied between wetland types. This knowledge has implications for wetland management and conservation, as sub-tropical wetlands are particularly vulnerable to degradation through cultivation, and they are found in some of the most densely inhabited rural areas of South Africa. The research also improves our understanding of the complexities of wetland delineation on sandy aquifers, and the links between vegetation, substrate characteristics and hydrological regimes.

Wetland researchers, hydrologists and, more recently, colleagues in the hydropedological field – an emerging field formed by a combination of soil science (or pedology) and hydrology (van Huyssteen et al., 2005*) – have expanded on the links between the wetlands and the hillslopes that supply water to them, through a number of WRC-funded research initiatives. Lorentz (2001*) identified and described the dominant hydrological processes along hillslopes, and quantified these for inclusion in hydrological models (Lorentz et al., 2007*). Van Huyssteen et al. (2005*) established the links between soil profile morphology and the soil water regime, and how these impact the hydrograph lower down the catchment. Le Roux et al. (2010*, 2011*, 2015*) improved on the conceptual hydrological response models for hillslopes, using soil properties, soil horizons, and soil types. Job et al. (2019*) then firmed up the logical link between wetlands, as the "signature of the hydrological dynamics in the surrounding catchment", and the terrestrial components of the catchment. This work highlights the importance of considering land uses within the broader catchment and how these affect hillslope hydrology, water sources and water delivery zones within the catchment, in order to better manage and conserve the wetlands that receive this water. The researchers on this WRC-funded project (Job et al., 2019*; Job and Le Roux, 2019*; van der Waals, 2019*) state that their work lays a critically important foundation for future expansion of the field of wetland identification and delineation.

Figure 3. Swamp forest on the Maputaland Floodplain. (Credit: Lulu Pretorius).

Wetland biota

Research into the taxa that live in and around wetlands in South Africa has been sporadic and thin on the ground. This has generally been the domain of SANBI, universities, conservation agencies and organisations such as the Endangered Wildlife Trust. The WRC has played a role in funding some of this research, but knowledge of the distribution, diversity, endemism, dynamics and interactions of South African wetland fauna and flora is poor. Surrogates for wetland biotic diversity are frequently turned to, such as wetland type or wetland vegetation type – for instance, the national wetland vegetation database established by Sieben et al. (2014*) – rather than being able to quantify true biotic diversity. A noteworthy contribution by the WRC to knowledge of the distribution and taxonomy of South African freshwater invertebrates was made in a series entitled, ***Guides to the Freshwater Invertebrates of Southern Africa***, edited by Prof Jenny Day and others (Chapter 7).

Wetland vegetation has probably received the most attention. The WRC has contributed significantly to the development of identification guides for wetland plants (van Ginkel et al., 2011*) and freshwater algae (van Vuuren et al., 2006; Taylor et al., 2007*). Some studies have focused on specific plants – for instance, palmiet (***Prionium serratum***), the 'ecosystem engineer'. The robust species has earned this name as a result of its ability to slow down surface flows, and create wetlands. Tanner et al. (2019) focused on palmiet wetlands in their work, looking at the relationships between these highly threatened ecosystems (e.g., Rebelo et al., 2018) and the hydrological functioning of the wetlands and, more broadly, the catchment. They found that the palmiet wetlands studied were sustained by perennial sub-surface water sources, from groundwater (Nardouw and Peninsula Aquifers of the Table Mountain Group sandstones) and interflow (sub-surface flows in the vadose zone). Sustained base flows during the low-flow months, and high hydraulic connectivity between wetlands and their catchments were particularly important for the occurrence and health of palmiet.

Figure 4. Palmiet (Prionium serratum) in the Vyeboom wetland, Upper Sonderend River, Western Cape. (Credit: Kate Snaddon).

Amphibians feature regularly in the scientific and popular wetland literature (e.g. Channing, 1998; Tarrant and Armstrong, 2013; Vlok et al., 2013*). Around 84% of South Africa's frog species use wetland habitats to some extent (Channing and Van Dyjk, 1995) and it has recently been reported that almost 30% of South Africa's 135 frog species are considered threatened (Bonthuys, 2020*). Efforts are underway to encourage research and implement conservation actions, such as biodiversity stewardship programmes, to understand and protect the most threatened amphibian species.

Figure 5. The Cape River Frog – despite its name, it is a common sight in Cape wetlands. (Credit: Jeremy Shelton).

In recent work partly funded by the WRC, Grenfell et al. (2019) resolved the mystery of clay hummock formation in seasonal wetlands in the Drakensberg Mountains of KwaZulu-Natal. They suggested that a combination of the movement of water and sediment and earthworm activity has led to the formation of hummocks, and the accumulation of nutrients within these features. This interesting and unusual study forms part of the growing literature on wetlands in drylands (e.g. Tooth and McCarthy 2007), and the interactions between the biota adapted to these challenging conditions and the physical and chemical processes shaping these ecosystems and the services they provide (Tooth et al. 2015).

A lack of information on South Africa's Ramsar sites was highlighted by the Department of Environmental Affairs and the WRC as a priority research area in 2013 (Malherbe et al., 2017*). In particular, baseline data on diatoms, zooplankton, macroinvertebrates, fish and amphibians are not available for most of our Ramsar wetlands. Biotic surveys were completed at nine Ramsar wetlands in order to address the lack of data for these important sites (Malherbe et al., 2017*). The researchers found unique assemblages at these sites, sometimes even unique to depressions embedded within a larger wetland, such as at the Makuleke Wetlands in the Kruger National Park.

Wetland delineation

Wetland delineation aims to identify the outer extent of the temporary zone of a wetland, as a means of recognising the boundary between wetlands and terrestrial areas. This is important information for wise decision-making on regulating land-use around wetlands (Job, 2009*). Desktop delineation of wetlands involves the use of aerial or satellite imagery (monitoring section in this chapter) and other spatial datasets such as vegetation, geology, flow accumulation paths, and so on. The objectives of desktop delineation are generally to confirm wetland presence and to provide a low-accuracy map of wetland extent. Field delineation of wetlands is far more detailed and complex, allowing the practitioner to use indicators of wetland presence as signs of wetland occurrence and hydroperiod (DWAF, 2005). In particular, soil and plant indicators are the foundation of current wetland delineation protocols in South Africa. The WRC funded a project in the 1990s (Kotze et al., 1996*) that introduced and opened up the subject of classification of hydric soils, thus laying the foundation for using soil characterisation for wetland delineation.

Wetland soils are not always easy to identify and characterise, and the WRC funded a project in the Western Cape that addressed the soils that are difficult to delineate, in particular sandy soils and soils that are light in colour (Job, 2009*). The research identified other indicators to look for in order to assist with these specific cases, and also provided a list of difficult types and the approach to delineation that should be used in these cases. Day et al. (2010*) tackled the challenges of wetland identification in more arid parts of the country and developed a comprehensive description of biotic and abiotic wetland indicators that can be used in these areas, or in dry times of the year in mesic areas.

As mentioned above, the wetlands of Maputaland have also proved to be tricky to delineate based on soils – in research done recently, it was found that the traditional soil indicators were unreliable on sandy coastal aquifers, but that soil organic carbon and soil colour indices (certain combinations of the various components of soil colour) are viable additional indicators of hydroperiod and wetland boundaries in these cases. More research will be required to fully understand the application of these indicators (Pretorius, 2016; Pretorius et al., 2017).

Allied with wetland delineation is the need to identify an appropriate buffer distance to help protect a wetland. In response to this need, the WRC supported the development of an assessment procedure for determining appropriate buffer zones around rivers, wetlands and estuaries. The guidelines appear in two parts: (1) the Technical Manual, which includes the rationale for the approach taken, together with important supporting technical information (Macfarlane and Bredin 2016a*) and (2) the Practical Guide, which includes field sheets and practical guidance for collecting and interpreting relevant desktop and field information (Macfarlane and Bredin 2016b*).

Wetland inventory, classification and mapping

The concept of a national wetland inventory for South Africa has been the subject of several research projects and reports for over 20 years, drawing on similar projects implemented sometimes at smaller geographical scales. Begg (1988) and Dely et al. (1999) piloted this approach in the KwaZulu-Natal Province, while Cowan and van Riet (1998) and Dini et al. (1998) proposed a wetland inventory at the national scale (see also Dini and Cowan, 2001). The National Inventory Programme was initiated in the early 2000s by the then Department of Environmental Affairs and Tourism, in partnership with several government departments and organisations, including the WRC. The WRC also funded an economic and ecological evaluation of wetlands in the Upper Olifants River catchment (Palmer et al., 2002*), a component of which focused on wetland classification, mapping and inventory (Marneweck and Batchelor, 2002*).

The systematic classification of wetlands is central to the development of a wetland inventory, as it not only formalises the description of wetlands according to their biophysical characteristics and functional attributes but also provides a framework within which the diversity of wetlands can be described and quantified. Reviews of the development of wetland classification systems in South Africa are provided by Ollis and Ewart-Smith (2006*) (provided as an appendix in Ewart-Smith et al., 2006*) and Ollis et al. (2015). Early ideas about wetland classification systems were refined over time into a six-tiered national classification system for inland aquatic ecosystems founded on the hydrogeomorphic characterisation of wetlands (Ewart-Smith et al., 2006*; Ollis et al., 2013, 2015). This classification system makes reference to approaches that may have focused on specific aspects of wetland classification, but which have applicability across the country, such as Kotze et al.'s (1994*) wetland soils classification system for Kwazulu-Natal, Marneweck et al.'s (2001) classification of peat wetland ecoregions, and the hierarchical national wetland classification systems developed by the national Department of Environmental Affairs (e.g. Dini et al., 1998; Dini and Cowan, 2001). More recent work has focused on the classification and analysis of wetland vegetation types, and the development of bioregional wetland floras for southern Africa (Sieben et al., 2014*; Sieben et al., 2021), while Grenfell et al. (2019) have proposed a classification of wetlands that focuses on the mode of wetland formation and the occurrence of geomorphic characteristics indicative of landscape processes.

Figure 6. A typical seep on a slope in the mountains of the Western Cape, showing clear zonation of wetland vegetation communities. (Credit: Kate Snaddon).

Ephemeral and/or endorheic depressional wetlands, or 'pans' as they are more commonly called, occupy a unique and sometimes contested space within wetland classification systems. These interesting ecosystems confound systematic classification, as they often do not display indicators of wetland presence (e.g. hydric soils, wetland vegetation, wetness), or these characteristics are fleeting and rare. The WRC review of pans (de Klerk et al., 2016a*) adopted the simple classification of pans proposed by Allan (1987) who identified five types of pans based broadly on vegetation (see also Allan et al., 1995; Cowan and Van Riet, 1998). De Klerk et al. (2016a*) found that pH and Electrical Conductivity added a useful tier to pan classification. Henri et al. (2014*) explored the use of water quality parameters as a means of classifying endorheic wetlands, but found that the inherent temporal and spatial variability in these parameters was too great to accommodate the systematic classification of these ecosystems. This variability was also echoed in the high diversity of Branchiopoda (e.g. fairy shrimps) that were successfully hatched from pan sediments.

The fact that many of South Africa's wetlands spend much of their time dry presents challenges to those who attempt to describe, classify and assess them. Day et al. (2010*) advanced the methods used for the delineation and assessment of temporary wetlands during dry conditions by providing lists of plant and invertebrate species that are typical of these 'cryptic' ecosystems. They also prescribed a method for the sampling and hatching of desiccated propagules of temporary wetland invertebrates.

Figure 7. Vegetation on the margins of an ephemeral pan (depression) in the Northern Cape. (Credit: Kate Snaddon).

Wetland mapping has advanced significantly over the past five years (Mbona et al., 2019). The main impetus behind this development was spatial planning, where the need to produce conservation plans for cities, municipalities, and provinces drove the growth in this skill-set. With time, wetland maps became embedded in other contexts, such as the National Freshwater Ecosystem Priority Areas (NFEPA) project (Driver et al., 2011*; Nel et al., 2011*) – part-funded by the WRC – and SANBI's National Biodiversity Assessments (done in 2011, 2019). The WRC published wetland mapping guidelines (Mbona et al., 2015*) for the refinement of spatial wetlands data, specifically to support decision-making for coal mining in the Mpumalanga Highveld. This sub-region contains one of the highest concentrations of FEPAs and mapped wetlands in the country, with a unique association between wetlands and grasslands. This area also collectively contains 51% of the national recoverable coal reserves, so the pressure on wetlands – where significant coal reserves are found – is immense. The WRC also co-funded a High Risk Wetland Atlas for the Mpumalanga Highveld (Holness et al., 2016*), which aimed to identify key wetland landscapes that are important for biodiversity conservation, water resource management and other ecosystem services. The Atlas allowed users access to the underlying spatial data, such as the wetland map.

Figure 8. The High Risk Wetland Atlas publications, published by the WRC in 2016.

Currently, the most accurate map of the wetlands of South Africa is National Wetland Map 5 (van Deventer et al., 2019).

This map, developed for the National Biodiversity Assessment (NBA) of 2018, shows that the wetlands of South Africa cover 2.6 million hectares, representing 2.2% of the country's surface. Despite a significant improvement in wetland mapping over the past five years, the NBA concluded that wetlands are still under-represented on the National Wetlands Map, that 79% of South African wetlands are threatened (i.e. Critically Endangered, Endangered or Vulnerable), and that only 6% are well protected.

Assessing wetland health and provision of ecosystem services

Wetlands represent ecological infrastructure that can potentially contribute important ecosystem services to several national imperatives, including: (1) water resource management; (2) biodiversity conservation; (3) human safety and disaster resilience; (4) socio-economic development and poverty elimination; and (5) mitigation and adaptation to climate change (Kotze et al. 2020a*, 2020b).

Every wetland is therefore likely to be of some importance. Individual wetlands differ greatly, though, according to their Present Ecological State (PES) (often referred to as ecosystem condition or health), and the degree to which they supply ecosystem services to society. Central to wetland management, conservation and decision-making in South Africa is the assessment of a wetland's PES and its ecological importance, of which ecosystem service delivery is a major component. Furthermore, assessing the PES of an aquatic ecosystem is also a legal requirement for a number of water resource management processes, notably those established through the National Water Act (Act No. 36 of 1998). A chronological review of the PES (and other) assessment methods developed in South Africa was done by Ollis and Malan (2014*), as part of a WRC-initiated project to develop a decision-support protocol for the assessment of wetland PES (see Ollis et al., 2014*).

Recognising the need to make these assessments, the first versions of WET-Health (Macfarlane et al. 2009*; Kotze et al. 2012) and WET-EcoServices (Kotze et al. 2008a*) were developed with the aid of funding from the WRC. Both of these techniques have since been applied widely within South Africa as well as further afield, mainly in other African countries (Namaalwa et al. 2013; Rebelo et al. 2013; Cowden et al. 2014). Some of the applications of the techniques include: building knowledge and competency, particularly among young practitioners; (2) rehabilitation planning within Working for Wetlands (see the following section); and (3) use in conducting environmental impact assessments and state of the environment reports, water use licensing and water Resource Quality-Objective assessments.

Over the last decade, the understanding of how wetlands function, how they respond to degradation, and how they supply services to society has advanced. In addition, relevant new datasets have become available, and many lessons have been learnt through the wide application of the two techniques, as well as others. Thus, the first versions of the two techniques have recently been refined and revised to produce WET-Health Version 2 (Macfarlane et al. 2020*) and WET-EcoServices Version 2 (Kotze et al. 2020a*, 2020b).

WET-Health Version 2 attempts to account for some of the key interacting processes that take place within a wetland by evaluating four inter-related components – hydrology, geomorphology, water quality, and vegetation. The technique allows for three different levels of resolution:

- Level 1: desktop-based, low resolution, which uses only pre-existing landcover data;
- Level 2: desktop-based, high resolution, which makes finer distinctions than the Level 1 tool in terms of landcover types; and
- Level 3: rapid field-based assessment, which poses a suite of site-based questions.

It is important to note that the biotic component of WET-Health relies on subjective scoring of the vegetation (albeit with guidelines to promote consistency). The WRC has previously funded several projects aimed at developing more objective bio-assessment methods for a range of taxa, including vegetation (Corry 2012*), diatoms (Matlala et al. 2011*) and macroinvertebrates (Bird 2010*). All of these studies contributed to an enhanced understanding of the relationship between these different taxa and the level of degradation for certain bioregions. However, none was able to provide a fully developed and tested method with wide applicability in South Africa, which likely relates at least partly to the considerable heterogeneity of South Africa's wetlands. Further research is needed on this topic.

In addition to assessing ecological health at individual sites, there is also a need to undertake such assessments at a landscape scale for broader regional planning. This was the motivation behind a WRC project to develop probability models of degradation per wetland type using landscape-scale predictor variables. Based on verification against a set of field-assessed wetlands, the study demonstrated that for KwaZulu-Natal, factors such as road density, population density and anthropogenic land use were valuable predictors of wetland condition, and differed per hydrogeomorphic wetland type (Rivers-Moore and Cowden, 2012*).

WET-EcoServices Version 2 includes the assessment of sixteen different ecosystem services which encompass regulating and supporting services (e.g. sediment trapping and flood attenuation), provisioning services (e.g. provision of natural resources for human use) and cultural services (e.g. tourism and recreation). A set of indicators are scored that reflect the supply and demand for each ecosystem service. A key change made to Version 2 was expanding the technique to include non-wetland riparian areas.

WET-EcoServices is not designed for economic valuation of wetlands, for which a WRC-funded protocol was developed by Turpie and Kleynhans (2010*), together with a number of case studies (Turpie and Malan 2010*). One of these is an estimation of the water quality amelioration function and value of wetlands in the Western Cape (Turpie et al. 2010*). Another example is the valuation of the provisioning services of contrasting examples of a rural wetland in Lesotho and a peri-urban wetland in South Africa (Lannas and Turpie 2009). The ecosystem services approach was also applied in a WRC-funded project that demonstrated the socio-economic value of South African peatlands (Mulders et al. 2017*). The assessment focused on the estimation of carbon accumulation rates and current carbon stocks in peatlands, which were conservatively estimated to be worth more than R13 billion.

People's livelihoods depend on many South African wetlands, while people also have the potential to degrade them. There is thus a need to support the sustainable management of wetlands. In response to this need, the WRC has supported various research initiatives, including: (1) a review of agricultural land-use impacts on wetland functional values (Kotze and Breen 1994*); (2) a wetland management decision support system for the KwaZulu-Natal midlands (Kotze et al. 1994*); (3) the development of sustainability indicators in communal wetlands and their catchments (Pollard et al. 2009*); (4) WET-SustainableUse (Kotze 2010*), which provides specific guidance for assessing grazing of wetlands by livestock, the cultivation of wetlands and the harvesting of wetland plants for crafts and construction, and (5) WET-WELL (Hay et al. 2014*), a handbook which, together with background information and case studies provided in Hay (2014*), is designed to assist anyone who is supporting a management process at a wetland in South Africa where a particular focus is the contribution to human wellbeing.

Figure 9. Harvesting of reeds in wetlands, Maputaland. (Credit: Lulu Pretorius).

Wetland monitoring

An assessment of the impact of WRC-funded wetland research in 2010 identified the need for a national wetland monitoring system (Phillips and Madlokazi, 2010*). Consequently, the WRC collaborated with the DWS to design such a system, the National Wetland Monitoring Programme (NWMP). The resulting two-volume report provides an account of the procedures and decisions made in developing the NWMP, and a detailed description of the three-tiered approach to wetland monitoring, as well as methods for collecting the data (Wilkinson et al., 2016b*). Although monitoring is mandated by the NWA, implementation of the NWMP has been slow, partly due to a lack of funds and capacity in government. Wetlands are currently being identified in each of the provinces for pilot studies.

Bredin et al. (2019) developed an approach for the step-by-step development and monitoring of wetland Resource Quality Objectives (RQOs), following the gazetting of the RQO process in 2010. The approach focuses on determining primarily qualitative, or at best semi-quantitative, RQOs for priority wetlands across the country. The approach will ultimately complement the NWMP when it is implemented, and it is essential that the NWMP align with RQO monitoring, so that efforts can be synchronised.

One of the country's few monitoring projects that surveyed wetlands at a regional scale was Silberbauer and King's (1991a, 1991b) work on the wetlands of the south-western Cape. The WRC funded a follow-up study, looking at trajectories of change in wetlands of the Fynbos Biome over time (Malan et al., 2015*). Most of the wetlands visited in the initial study remained the same or improved in terms of both ecosystem health and conservation status, although a small number of wetlands have been lost entirely.

WRC-funded research has advanced our understanding and use of remote sensing imagery for monitoring wetlands. Van Deventer et al. (2020*) recently investigated the capabilities of remote sensing imagery and data that are feely available to the public to assist in wetland mapping and monitoring. They found that Sentinel sensors can make a valuable contribution to wetland mapping and monitoring, and that freely available sensors with a spatial resolution of ≥ 10m can detect almost 70% of the known aerial extent of wetlands. In the authors' opinion, the only challenge remaining is to secure funding for the implementation and operation of a remote sensing monitoring system for South African wetlands.

Recognising that wetland monitoring should not be the exclusive domain of professional scientists and technicians, the WRC supported a project to develop appropriate citizen science tools, interventions and social processes so as to better respond to the challenges around water resources, including wetlands (Graham and Taylor 2018*). Several readily accessible tools, such as the Water Clarity Tube, were developed and packaged into an integrated water resource and catchment monitoring toolkit, known as 'Capacity for Catchments' (Graham and Taylor 2018*).

Wetland rehabilitation

With the establishment in 2000 of the Working for Wetlands (WfW) Programme, the number of wetlands being rehabilitated in South African rapidly increased. The rehabilitation of wetlands is often complex, however, and at the time there was limited expertise on which to draw. This led to the development of a series of tools, co-funded by the WRC and the Department of Environmental Affairs and Tourism's WfW Programme. The tools were designed to assist wetland rehabilitation in a well-informed way, both within the WfW Programme and beyond, and included:

- *WET-Origins* (Ellery et al., 2009*) described in Section 3. The report provides a methodology for using knowledge of a wetland's origin and the geological and geomorphological processes that influence its functioning within the landscape, to inform the most appropriate rehabilitation interventions.
- *WET-RehabPlan* (Kotze et al. 2008b*) provides a process for undertaking the planning and implementation of wetland rehabilitation at a range of scales from national/provincial to local.
- *WET-RehabMethods* (Russell, 2008*) is designed to guide the selection and implementation of rehabilitation methods that are appropriate for the particular problem being addressed and for the wetland and its catchment context. It focuses particularly on wetlands associated with natural drainage networks and includes: (1) key concepts relating to wetland degradation, particularly erosion; (2) guidelines for the selection of an appropriate type of rehabilitation intervention (including both 'soft' and 'hard' engineering options); (3) detailed guidance for designing a wide variety of intervention types (e.g. determining an adequate spillway to account for runoff intensity); and (4) detailed guidance for implementing the different intervention types.
- *WET-RehabEvaluate* (Cowden and Kotze 2008*) is designed to evaluate the success of rehabilitation projects, with the understanding that monitoring and evaluation are closely tied to planning. The tool has recently been refined and expanded as WET-RehabEvaluate Version 2 (Walters et al. 2020*) which includes, amongst other additions, more explicit coverage of different potential assessment criteria and assessing wetlands as social-ecological systems, together with a set of detailed case examples.

Figure 10. The WET series of guides for wetland rehabilitation.

The above tools have been applied extensively within the Working for Wetlands programme. In one particular application, WET-RehabEvaluate, WET-Health and WET-EcoServices were applied in the assessment of the long-term ecological outcomes at nine wetlands (one from each of South Africa's provinces) with most sites having been rehabilitated more than 5 years before the post-rehabilitation assessment (Kotze et al. 2020a). This provided a useful means of comparing the change in ecological health, which for most of the sites improved by 10-30%. Based on the spatial extent of each wetland, improvement in ecological health was expressed as hectare equivalents. Then based on the costs of the rehabilitation interventions at each site, cost-effectiveness was reported in Rands per hectare equivalent restored, which interestingly was found to vary by more than an order of magnitude across the wetlands. By also considering the effects of the rehabilitation on the supply of ecosystem services, useful overall comparisons could be made and lessons learnt, considering the specific contexts of the sites and their rehabilitation issues.

In addition to the tools, the WRC has also supported detailed primary research on individual wetland rehabilitation sites, such as geomorphological origin and evolution studies at a wetland in the KwaZulu-Natal Drakensberg foothills (Grenfell et al. 2009) and at the Wakkerstroom wetland in Mpumalanga (Joubert and Ellery 2013). This primary research also included a hydrological monitoring study of the shallow groundwater feeding into the Manalana wetland in Limpopo Province (Riddell et al. 2012; 2013), which showed that the wetland's hydrodynamics were effectively restored following rehabilitation (Riddell et al. 2012). An assessment of the social and economic contribution of the rehabilitation work to the livelihoods of small-scale farmers dependent on the rehabilitated wetland (Pollard et al. 2008*) showed that the annual value of livelihood benefits from the degraded wetland was 34% of the rehabilitated wetland. Furthermore, the net present value of the livelihood benefits provided by the rehabilitated wetland over a 50-year period (R1 995 885) is more than double the cost of the rehabilitation interventions (R947 328), indicating a very favourable return on investment. A follow-up assessment 10 years after the initial post-rehabilitation assessment, reported in Walters et al. (2020*), revealed that both the ecological health of the wetland and its livelihood contributions have been sustained over this period.

Rehabilitation also has the potential to greatly influence the regulating services provided by wetlands, as demonstrated in a WRC-supported assessment of the Zaalklapspruit wetland. The assessment showed that rehabilitation undertaken at the site, in partnership with WfW, contributed significantly to reducing metal pollution and water acidity arising from upstream coal-mining activities (De Klerk et al., 2016b; Oberholster et al., 2016*).

Figure 11. A Working for Wetlands rehabilitation site at Zaalklapspruit, Mpumalanga. (Credit: Donovan Kotze)

Environmental flows and the Ecological Reserve

The WRC has initiated a number of projects and conferences focused on environmental water requirements (EWR), as mandated by the National Water Act (Winter, 2009*). Few of these have focused specifically on wetlands. Malan and Day (2005b*) addressed wetland water quality and the Ecological Reserve, with the aim of improving the tools and methods available for the determination of the Ecological Reserve for wetlands. Building on this research, a method was developed by Malan and Day (2012) that allows for the assessment of the PES of a wetland, based on its water quality, as part of the Ecological Reserve determination process. These projects provided valuable information which has been developed further in more recent WRC-funded projects, including the NWMP technical manual (Wilkinson et al., 2016b*).

Through a joint Department of Water Affairs and WRC initiative, a manual was developed to provide the technical information for Reserve determination for inland wetlands at a rapid level (Rountree et al., 2013*). The manual includes guidance on selecting the relevant specialists, based on considerations such as wetland type and hydrological complexity and the likely ecological and social importance of the wetland. Further guidance is provided for field assessments and determining Ecological Water Requirements of the wetland, i.e. how much water, and of what quality, should remain in the system. This includes determining how the flow quantity and pattern have changed over time and how to translate the preceding hydrological understanding into ecological impacts under current and future scenarios for the wetland system being assessed.

An environmental flows (EFlows) assessment, undertaken as part of Ecological Reserve determination studies for selected surface water, groundwater, estuaries and wetlands in the Usuthu/Mhlatuze Water Management Area (Brown et al., 2018), provides a rare example of specific consideration of wetlands in such an assessment. Although not a WRC-funded project, the results were reported in ***Water SA***, including recommendations for modified releases from the Jozini Dam to support the socially, economically and ecologically important Pongola Floodplain downstream of the dam.

Grenfell et al. (2005) examined the concept of wetlands as effective, early indicators of hydrological change at the catchment scale, by monitoring a hillslope seep wetland in KwaZulu-Natal following afforestation of the upstream catchment with pine and eucalyptus. They found that afforestation led to substantial decreases in stormflow runoff, leading to shifts in the vegetation communities inhabiting the wetland. They concluded that monitoring wetland vegetation is an effective means of determining, implementing and monitoring the Ecological Reserve for wetlands.

Wetlands and climate change

Inland aquatic ecosystems are globally considered to be vulnerable to climate change, and southern Africa specifically has been identified as a water-related vulnerability 'hotspot' in terms of climate change (Snaddon et al., 2019). It is therefore crucial to consider wetlands, as integral components of the water cycle, especially in a semi-arid country like South Africa, when thinking about climate change and water. Even more so is the urgency since, according to Tooth (2017), studies on the resilience of wetlands to climate change have been restricted to more-or-less permanently saturated systems. There is thus a lack of information on the resilience of seasonal and temporary wetlands (which are more common than permanent wetlands in South Africa), despite these ecosystems often delivering significant environmental functions and ecosystem services.

The WRC has funded numerous studies on climate change in general, notably a comprehensive research portfolio on the water-resource impacts of climate change (see also Chapter 12). This work mostly focused on defining a framework for research and development needs in the water sector (Green, 2008*), and wetlands were briefly mentioned as a priority for the identification and quantification of ecosystems impacted by climate change, and to how to deliver on climate change adaptation outcomes in South Africa.

To date, there has only been one WRC-funded study explicitly addressing wetlands and climate change – that of Schael and Gama (2019*). Their study focused on the sensitivity of ephemeral wetlands to climate change. Specifically, the project looked at the biogeochemical cycling of primary producers and the effect of different levels of inundation, temperature and nutrient regimes on lower trophic level relationships. It also modelled climate change-induced changes in ecosystem services supplied by ephemeral wetlands in peri-urban and urban environments.

Constructed wetlands

Some of the ecosystem services provided by wetlands can be emulated to some extent with constructed wetlands. Water and wastewater treatment processes are typical applications of this concept and the WRC leads the way in funding such research in South Africa. In 1988, the WRC and the CSIR worked with consultants to develop engineering guidelines for the design and use of constructed wetlands for the treatment of domestic wastewater (Wood and Pybus, 1993*). The study included an economic appraisal of the use of constructed wetlands for the treatment of raw sewage, the removal of nutrients and suspended solids from partly treated activated effluents, and the polishing of oxidation pond effluent. At the time, the construction of constructed wetlands leant heavily on designs from other countries, with many assumptions made in their application to the South African environment. In many cases, this resulted in failure to meet design objectives, thus limiting the acceptance and spread of the technology. In the late 1990s, the WRC funded a project to investigate the application and performance of constructed wetlands for wastewater treatment in South Africa (Wood, 1999*). An important finding was the need to control the hydraulics of the system to optimise retention times and contact opportunities for effective treatment.

Constructed wetlands are now used successfully for the treatment of a wide range of wastewaters, from wineries (Burton et al. 2007*, 2012*; Welz et al., 2015) and breweries (Jones et al., 2014*), to mines, agriculture, and a variety of industries (Jones et al., 2014).

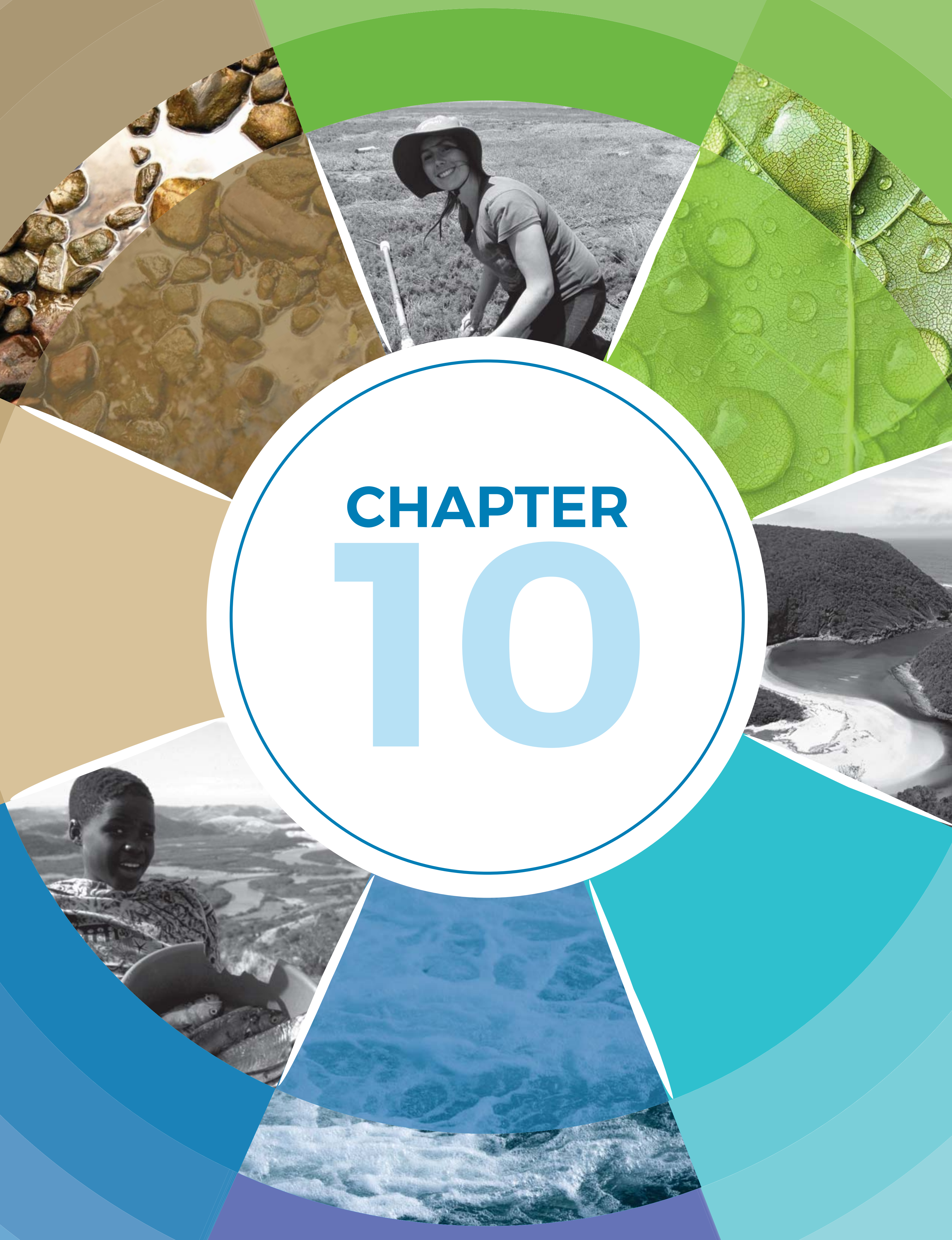
Wetlands are also now being constructed in order to restore wetland functions within urban catchments, as drinking holes for game, for flood attenuation, and for aesthetic reasons. A WRC project – 'Biomimicry and Wetlands' – looked broadly at the roles that wetlands perform in the natural environment and how these can be mimicked for human use (Dama-Fakir et al., 2018*). Their work focused on constructed, or treatment wetlands, and they identified a major challenge in their application – contaminant loads produced by humans far exceed those occurring naturally. They conclude that biomimicry can be used to solve the challenges that nature has solved through adaptation and evolution.

Looking to the future

The wetland scientist and practitioner community is a relatively small group in South Africa. Wetland research has, nonetheless, made substantial and sustained progress over the past 40 years or so, in many ways thanks to the WRC. The Commission has supported the wetland community and contributed towards the growth of wetland science and practice. This has taken the form not only of research funds and platforms for publication, but of financial and technical support for formalising the field of practice, hosting the annual National Wetlands Indaba, and sponsorship of students. These contributions cannot only be recorded in monetary terms, numbers of reports and publications, or even as research findings, but also in terms of the cohesion and energy that exists within the wetland community.

Turning to significant milestones reached and future needs – more than 20 WRC-supported wetland assessment and management tools have been developed. Although several of these have been field-verified and refined, there has been almost no research on the application of these tools. This is required in order to better understand who is using the tools, how they are being applied, and to what extent they are building knowledge and supporting sound wetland management and conservation decisions. This is identified as a critical need. It is further recognised that any tool is only as good as the scientific knowledge base on which it draws, highlighting the need to continue investing in primary research on South Africa's wetlands. Of particular importance will be research directed at understanding the hydrological, geomorphological and biotic functioning of the diversity of South Africa's wetland types, faced with escalating environmental change. Furthermore, this research will need to account for the key competing social demands that are made on wetlands.

True to their definition, wetlands lie in a contested space that is transitional between the aquatic and terrestrial realms. This complexity presents a challenge, but with the wise application of research funding, an improved understanding of wetland dynamics will lead to better management, and conservation of these threatened ecosystems.



CHAPTER 10

THE CONTRIBUTION OF THE WRC TO ESTUARINE RESEARCH IN SUPPORT OF EFFECTIVE POLICY DEVELOPMENT AND RESOURCE MANAGEMENT

Lara van Niekerk, Janine Adams, Susan Taljaard, and Stephen Lamberth

INTRODUCTION

South Africa has 290 estuaries and 42 micro-estuaries which have been classified into 22 estuarine ecosystems and 3 micro-estuary types. This represents a high diversity of estuary types stemming from the country's diverse climatic, oceanographic, and geological drivers. Four biogeographical regions characterise the South African coast; namely the Cool Temperate (Orange to Ratel), the Warm Temperate (Heuningnes to Mendwana), the Subtropical (Mbashe to St Lucia) and the Tropical (uMgobezeleni to Kosi) (van Niekerk et al 2020). South Africa's comparatively small, wave-dominated estuaries generally have restricted inlets, with more than 75% closing for varying periods when a sandbar forms across the mouth. These highly productive ecosystems support a wide array of ecosystem services of great social (e.g., recreational), economic (e.g., fisheries) and climate regulatory (e.g., carbon sequestration) value (Van Niekerk et al. 2019).

Transition into a democracy (mid-1990s) led to the development of numerous new environmental policies and statutes promoting a more holistic, participatory approach to the management of natural systems such as estuaries, and posed new challenges for government, civil society, and researchers. Two pieces of legislation, the National Water Act (No. 36 of 1998) (NWA) and the National Environmental Management: Integrated Coastal Management Act (No. 24 of 2008) (ICM Act), greatly influenced the move from a largely disciplinary-based focus to a more integrated multidisciplinary approach. For example, the NWA gave aquatic life a 'right to water' which required estuarine science to direct their efforts to ecosystem-based research, rather than discipline-based. In the case of the ICM Act, the need for cross-sectoral integrated management estuarine also required research into innovative science-based solutions across a range of estuary types and pressures (e.g., land-use, fishing, pollution).

The Water Research Commission (WRC) has been a staunch and enduring funder of estuarine research in South Africa, with support ranging from identifying research gaps, to the development of dedicated research programs, student advancement, capacity building and funding the development of policy and management tools.

In drafting this overview, we have largely drawn from our experiences as students, participants, project leaders and steering committee members of a number of WRC projects. We have supported our experiential knowledge through a literature review to ensure that key outcomes were captured. The intent here is not to reflect all contributions through the decades, but rather to identify seminal research outputs that have resulted in clear policy and management interventions, or key research 'stepping stones' in the generation of new insights and knowledge on estuaries.

In particular, we focus on the research that built multi-disciplinary understanding on estuarine ecosystem function, development of environmental water requirement methods, science that has contributed to integrated estuarine management, developments in estuarine monitoring in support of policy and management, and estuarine resource use and quantification of benefits. Finally, we touch on restoration, an emerging field of research supported by the WRC, and conclude with ideas on the role of the WRC in advancing future research in support of the protection and management of our valuable estuarine resources.

Figure 1. South Africa has 290 estuaries and 42 micro-estuaries. (Credit: NMMU/Water Wheel archives)

Building multidisciplinary understanding on estuarine ecosystem function

> **Key outcome 1:** River-estuary-interface (REI) zone was recognised as an important source of primary production (food) and nursery area (invertebrates and fish). Loss of this critical zone directly impacts the overall health and productivity of a system.

Over the last three decades, the WRC has funded several multi-institutional, multidisciplinary research studies that have contributed to the improvement of our understanding of how estuaries function and how to transfer this scientific understanding into Ecological Water Requirements (EWR) method development and estuarine management. Much of this work was done through the Consortium for Estuarine Research and Management (CERM), which was a group of interested people collaborating on the wise management of estuaries.

Numerous workshops were held over the years to identify research projects where CERM members could co-operate. Key studies include the effects of a dam release into the Kromme Estuary (Bate & Adams 2000*; Wooldridge, and Callahan, 2000), the importance of the river-estuary-interface zone in the Gamtoos Estuary (Bate et al. 2002*; Whitfield & Wood 2003*) and the environmental water requirements of the East Kleinemonde Estuary (Whitfield et al. 2007*, 2008; Whitfield and Bate, 2007*; van Niekerk et al. 2008*; Turpie et al. 2009a*, 2009b*, 2009c*; Wood, 2010*). Many post-graduate students were involved in this research.

For example, seminal research was undertaken on the river-estuary-interface (REI) zone by a multidisciplinary team in the Gamtoos Estuary, with the REI zone defined as 'that part of the estuary where the river and estuarine water mix, and where the vertically integrated salinity is usually less than 10'. This study showed that while the structure and function of the REI zone was primarily governed by the quantity and quality of the freshwater it received, it strongly influenced the physico-chemical as well as biological structure and function of the entire estuary. Before this study, it was generally seen as a positive aspect if the salinity profile moved upstream as a result of flow reduction or mouth manipulation, with scientists interpreting it as 'increasing the estuarine area'. Post this study, the REI was recognised as an important source of primary production (food) and nursery area for invertebrates and fish. Loss of this critical zone directly impacts the overall health and productivity of a system (Bate et al. 2002*; Whitfield & Wood 2003* Ecological Water Requirements).

A release of freshwater from the upstream Mpofu Dam (2×10^6 m^3 < 2% of the natural mean annual runoff) to the Kromme Estuary showed that there was little salinity mixing and instead of a once-off pulse consistent baseflow would be needed to maintain a longitudinal salinity gradient and a productive REI zone (Bate & Adams 2000*).

Figure 2. East Kleinemonde Estuary. (Credit: NMMU/Water Wheel archives)

While earlier research tended to focus on permanently open estuaries, subsequent studies recognised that little was known about the multiple small temporarily-open estuaries that dominate South Africa's coast. In 2005 /2006 a multidisciplinary research programme was conducted on the Kleinemonde Estuary, including investigations into the hydrodynamics, sediment dynamics, water quality, microalgae, macrophytes, invertebrates, fish and birds of the system (Whitfield et al. 2007*, 2008; Whitfield and Bate, 2007*). Particular attention was given to the responses of the different ecosystem components to the opening and closing of the estuary mouth and how this is driven by both riverine and marine forces. Using a complementary dataset of daily estuary mouth conditions spanning a 14-year period, distinct phases of the estuary were identified, including closed, over-wash from the sea, outflow, tidal and semi-closed. The open-mouth phase was critical as it provided estuary-sea connectivity for a range of fish and invertebrate species. The timing of the open phase also has a strong influence on the ability of estuary-associated fish and invertebrates to recruit into the system, with a spring opening (October/ November) regarded as optimal for most species. The type of mouth-breaching event and outflow phase determined the subsequent salinity regime. A deep mouth breaching following a large river flood leads to strong tidal exchange and a more saline estuary. Conversely, a shallow mouth breaching with restricted tidal exchange resulted in a fresher estuary. The biota, especially the submerged macrophytes, respond very differently to the above two scenarios. Whilst birds were less sensitive to mouth state, consistent slight increases in piscivorous and resident wading bird species were observed when the estuary mouth opened, possibly linked to increased feeding opportunities during that phase.

Research capacity was extended to KwaZulu-Natal through joint research and specific studies on the small uMdloti and uMhlanga estuaries (Perissinotto et al. 2004*; Lawrie et al. 2010). An interesting finding was that the small temporarily closed estuaries of KwaZulu-Natal tend to be more productive during their closed phase than under open conditions. This was attributed to the perched (elevated above sea level) location and the high river flow that facilitates open conditions. During the open state, these systems can drain between more than half of their water column area (Perissinotto et al. 2004*; Lawrie et al. 2010). In contrast, mouth closure cuts off tidal exchange with the ocean, resulting in prolonged periods of stable conditions during which salinity and temperature stratification may develop, along with oxygen and nutrient depletion. Microalgae are key primary producers in small temporarily closed estuaries, and while phytoplankton biomass in these systems is usually lower than in permanently open estuaries (Gama et al. 2005*), microphytobenthic biomass is often much higher. This is during the closed phase when there is an absence of tidal currents, clearer water and greater light penetration. However, the prolonged period of mouth closure leads to poor levels of zooplankton diversity with only a few dominant species. Benthic meiofaunal abundance is usually greater during closed phases with nematodes dominant. Macrobenthic density, and occasionally even biomass, in small temporarily closed estuaries, is higher than in permanently open systems. These early studies lead to an improved understanding of the Ecological Water Requirements of closed estuaries globally (Adams and Van Niekerk 2020).

In response to the ongoing decline of South Africa's largest and most important estuary due to a combination of climatic (drought) and anthropogenic (diversion of Mfolozi from the St Lucia lakes) pressures, a national natural sciences workshop was hosted by the WRC that evaluated the divers of change, connectivity issues, and conservation requirement of this important wetland system (Whitfield, 2014*). Supporting this was a research review of all studies on the Mfolozi Estuary and associated floodplain, with an emphasis on the information required by management for future reconnection of the river to the St Lucia system (Bate et al. 2011*). These studies paved the way for the reconnection of the Mfolozi to the greater St Lucia Lake system.

Figure 3. The lower Mfolozi floodplain. (Credit: Ricky Taylor/ Water Wheel archives)

In addition, investment has also been made in supporting numerical tools, such as the hydrodynamic modelling of water quality parameters and the use of systems modelling tools (Slinger et al. 1998*). Research had shown that numerical modelling was one of the key techniques that support decision-making concerning the management of water quality globally as it serves a critical function in compliance testing, determining the fate of different water quality constituents in the environment, and established natural and ambient variability of different water quality parameters. Supporting this, a 1-dimensional numerical model, Mike 11, was tested in two permanently open estuaries, namely the Groot Berg and the Swartkops estuaries (Slinger et al. 1998*). Key parameters such as salinity, dissolved oxygen and turbidity were simulated with the model and validated against field data. From these small beginnings, Mike 11 became of one the key modelling platforms in estuary studies in South Africa. A number of WRC studies also focused on estuarine water quality in particular (e.g., Lord & MacKay 1993*; Pearce & Schumann 1997*; Wepener et al. 2006*).

Determination of ecological flow requirements for estuaries

The NWA (Protection of Water Resources) requires that a 'Management Class' (i.e., desired state), 'Reserve' (i.e., river inflow and quality) and 'Resource Quality Objectives' (i.e., desired condition of habitat and biota) be determined for all water resources in the country, including estuaries – this process or method referred to as Water Resource Classification.

Recognising that it would take time to develop a comprehensive Classification system, the act also made provision for Preliminary Reserve Determination until resources were available to undertake proper classification. Legally defensible methods for the determination of resource classes, the Reserve and Resource Quality Objectives had to be developed. Importantly, the government specified that the suite of methods should have ecological rather than purely hydrological or chemical endpoints. Soon after the promulgation of the Act, the national government commissioned studies to develop official methods for the determination of Ecological Water Requirements (EWR).

For estuaries, method development was undertaken by a core team of estuarine specialists in collaboration with members of the Consortium for Estuarine Research and Management (CERM) and supported by funding from the WRC. This development builds on methods previously applied in so-called Estuarine Freshwater Requirement (EFR) studies in the

1980s and 1990s before the promulgation of the NWA. The first EWR method for estuaries was published in 1999 (DWAF 1999). Since then, the EWR methods for estuaries underwent two main revisions, namely in 2008 (DWAF 2008) and in 2012 (Turpie et al. 2012a*), both supported with funding from the WRC.

Key aspects of these methods, for example, include the identification of typical abiotic states in estuaries linked to typical flow ranges – a critical requirement in EWR studies. An Estuarine Health Index was developed to standardise the assessment of Present Ecological Status (PES), as well as to assess the implication of future water resource scenarios on ecological health, measured as similarity to a Reference Condition (or the Natural State). The Reference Condition is hind-cast by a multidisciplinary group of estuarine scientists based on the present status of the estuary and knowledge of impacts that may have affected the system. A major challenge in developing an index for application in South Africa was not only related to the determination of appropriate criteria, their calculation and weightings, but also had to be robust enough to work with limited data (e.g., once-off measurements of abiotic or biotic aspects in highly dynamic estuarine ecosystems). For ecosystem health assessment it is important to recognise differences between dynamic and unidirectional change. Severe degradation in estuaries may involve a shift from dynamic change to dominantly unidirectional change so the loss of dynamic function per se may constitute degradation in estuarine health.

The Estuarine Health Index includes four abiotic (hydrology, hydrodynamics, physical habitat and water quality) and five biotic indicator components (microalgae, macrophytes, invertebrates, fish and birds). Expert and local knowledge, historical data and analysis of measured historical trends are all used to build a 'picture' of the probable reference conditions. Further, the EWR method includes an Estuarine Importance Index to standardise the assessment of biodiversity and conservation importance in South African estuaries. In this index estuarine importance is scored in terms of size, type and biogeographical zone, habitats and biota (plants, invertebrates, fish and birds). This method was applied nationally across all estuaries in 2002 (Turpie et al. 2002; Adams et al. 2004*; Turpie et al. 2004*). This study performed a complementarity analysis, incorporating data on abundance where available, to determine the minimum set of estuaries that includes all known species of plants, invertebrates, fishes and birds in South Africa, thus representing the first attempt at a national estuaries conservation plan. An estuary's importance status (including desired protected status) influences the overall choice of management class and hence its freshwater allocation. Finally, the method also provides criteria for the determination of a future, desired state (so-call Recommended Ecological Category) based on the PES and importance of a system.

Until 2015, the official methods for EWR determination only accommodated so-called Rapid, Intermediate and Comprehensive studies (requiring varying levels of data and confidence, as articulated in official documentation). However, with the ever-increasing demand for water resources, even less data-intensive planning tools for preliminary assessments were urgently needed. To address this gap a desktop method for EWR determination in estuaries was developed in 2015 (Van Niekerk et al. 2015*), funded as a research project by the WRC. This desktop method was primarily designed to perform high-level flow requirement assessments, relying on only available information and expert judgement. As a result, the method applies simple stochastic and rule-based models to assess abiotic indicators (hydrology, hydrodynamics, and water quality), and relies on readily available larger-scale data sets and expert opinion to assess biotic indicators. To ensure alignment with the overall EWR approach in estuaries, this desktop method applies the same indices and rules as the more detailed EWR method for estuaries under the NWA. The outcome of this project was also a Provisional Eco-Classification of the Cool and Warm Temperate Estuaries (~160 systems) along South Africa's coast aimed at providing water resource planners with regional-scale knowledge to inform strategic or preliminary planning processes pending the outcome of more detailed EWR studies.

Figure 4. The salt marshes at Langebaan. Open conditions are essential for maintaining the estuary's health as it promotes salt marsh growth and the recruitment of fish and invertebrates. (Credit: NMMU/Water Wheel archives)

To assist with the coordination of cross-sectorial management responses, key mitigation measures, subdivided into broad management sectors relating to water, land-use and development, and fisheries, were recommended. For example, catchment development and loss of connectivity between estuarine and upstream fish and invertebrate populations can be mitigated by well-designed fishways (Heath et al. 2005*). Subsequent to the original desktop method (Van Niekerk et al. 2015*), a water quality screening model has been developed aimed at standardising the determination of desktop water quality health as part of desktop assessments in data-poor environments (Taljaard et al. 2017*). Model outputs are derived from the proportional volume contribution of land-based flows (river inflows, diffuse inflows from the peri-catchment, point source discharges), with a water quality condition allocated to each of the inflows, and the output an overall water quality class for the estuary. The water quality assessment is based on readily available information such as land-cover data, legal limits for disposal, and water quality monitoring data, where they exist, making it suitable for a data-poor environment. These approaches were immediately adopted and formally implemented in the 'Classification of Water Resources and Determination of the Comprehensive Reserve and Resource Quality Objectives in the Mvoti to uMzimkulu Water Management Area' (DWS 2016) stressing the urgency for desktop methods and highlighting a successful science-to-policy cross-over.

The investment in EWR method development for estuaries by the WRC has delivered a substantial return. An assessment of completed detailed Ecological Water Requirement studies for South African estuaries (also funded by the WRC) showed that these methods have now been applied to more than 40% of all South African estuaries (Adams et al. 2016*), either as part of Preliminary Reserve Determination or Classification studies. Some of the methods and approaches developed have found much wider application in planning and biodiversity assessment. For example, the Estuary Health Index is now also widely used in National Biodiversity Assessments (e.g., Van Niekerk and Turpie 2012; Van Niekerk et al. 2019) and as input to South Africa's conservation planning (e.g., Turpie et al. 2012b).

Key outcome 2: Methods for the determination of Ecological Water Requirements for estuaries were first developed in 1999 soon after the promulgation of the NWA, and have since been applied in more than 40% of South Africa's estuaries as part of Preliminary Reserve Determination or Water Resource Classification Studies.

Advancing estuarine management – from science to practice

Since the advent of democracy in South Africa, there has been a strong emphasis on promoting the participation of civil society in governance and in managing the use of resources. The Eastern Cape Estuaries Management Research Programme was initiated in mid-1998 by the WRC to promote more effective management and sustainable use of estuaries in the Eastern Cape (Breen et al. 2004*; Mcgwynne et al. 2007*; Hay et al 2010*). The programme specifically supported research pertaining to local estuary management, institutional and policy development, and estuary management capacity building. Major challenges for the research team to address were understanding and acknowledgement of societal needs, how to give estuarine management a strong scientific base, and how to promote informed co-operative governance and management of estuarine resources.

Research findings showed that whilst policies and legislation exist to promote co-operative governance and estuarine management, this is frustrated by confusion about the roles of local government and civil society (Breen et al. 2004*). More particularly it is frustrated by the absence of formal delegation of responsibility and that there is a need for strategic guidance from national/provincial departments concerning estuarine management. Coastal municipalities were seen as pivotal in achieving the intentions of national and provincial policies and that their authority needs to be clearly defined and delegation must be formalised so that they can incorporate estuary issues into the integrated development planning process and be duly held accountable.

Figure 5. Traditional Tsonga fish traps built in the Kosi Bay estuary, Tongaland, South Africa. (Credit: 123RF stock photo)

In further support of estuarine management, a first-of-its-kind National Estuaries Workshop was held in Port Elizabeth in May 2002 under the auspices of the WRC and the national department of Environment Affairs. Managers and estuarine scientists all recognised the need for a more coordinated and integrated approach to the management of estuaries. Participants suggested that this could be achieved through the establishment of a National Estuarine Management Protocol that was flexible in approach, but binding in the need for collaboration (similar to the protocol that was in place for marine linefish at that time). Stemming from needs identified during this workshop research projects were commissioned by the WRC as part of the Eastern Cape Estuaries Programme to develop protocols for estuarine management, sustainable use, biodiversity, monitoring, rehabilitation and knowledge management, and their linkage to the Integrated Development Planning process.

One of the key outcomes of this programme was that those earlier drafts of the National Estuarine Management Protocol (van Niekerk and Taljaard, 2003*) were later refined and implemented at regional scales as part of the C.A.P.E. Estuaries programme (funded by Global Environment Facility: CSIR, 2009). Through ongoing engagement with the responsible government department, the above initiatives culminated in a dedicated chapter on estuaries in the ICM Act of 2008, as amended by the ICM Amendment Act (No. 36 of 2014) and the promulgation of South Africa's National Estuarine Management Protocol in 2013 (Regulations 341, Government Gazette #36432).

Key outcome 4: A dedicated chapter on Estuaries in the ICM Act of 2008 and the promulgation of the South Africa's National Estuarine Management Protocol in 2013.

Figure 6. WRC-funded estuarine research has led to the training of hundreds of students. (Credit: NMMU/Water Wheel archives)

To provide further support to estuarine management in South Africa the WRC funded the development of the first Estuarine Management Training Programme under the auspices of the Eastern Cape Estuaries Management Programme in 2006 (Van Niekerk, et al. 2006*). The course focused on estuarine ecosystem functioning, benefits of estuaries, management framework(s), monitoring, and the importance of dedicated estuarine management forums. From these early beginnings, the training course was further adapted and formally accredited through Nelson Mandela University (NMU). Since its inception, more than 250 students and managers have been trained by knowledgeable scientists and experienced estuarine managers from all over South Africa. Indeed, the value of this training programme is widely recognised by both national and provincial government to the extent that they were prepared to fund many of these annual events (e.g., CapeNature, SANParks, national Department of Environment and Western Cape Provincial Government) with in-kind contributions by NMU and CSIR. The next step will be to develop online training material and institution of virtual training programmes, a possibility for future WRC support.

Estuarine monitoring in support of ecological flow requirements and management

Sustainable management of estuaries cannot be achieved without appropriate and sound long-term environmental data. The need for a more multidisciplinary approach to estuarine research, also warranted a more integrated approach to environmental monitoring. However, long-term monitoring programmes are expensive and time-consuming, and careful planning is needed with respect to the design and implementation of such programmes to optimise benefits.

Earlier on in the roll-out of EWR studies (post-1999) the lack of sound long-term environmental monitoring data in estuaries became evident. Also, there were no formal procedures in place on the design and implementation of such long-term monitoring programmes in support of EWR studies and estuarine management. To address this urgent need, the WRC was approached in the early 2000s to fund the development of monitoring procedures for environmental monitoring for estuaries. As part of this study resource monitoring approaches were developed for both short-term baseline monitoring programmes (to characterise and understand the ecosystem functioning of a specific system), as well as and long-term monitoring programmes (e.g., for compliance assessment and tracking of possible trends). These procedures include a range of abiotic and biotic indicators used in EWR studies today (Taljaard et al. 2003*).

These monitoring procedures have since been adopted as the basis of South Africa's National Estuarine Monitoring Programme as illustrated here (Cilliers and Adams 2016).

Key outcome 5: Development of estuarine monitoring procedures applied in EWR studies, but also which underpins method adopted for South Africa's National Estuarine Monitoring Programme for South Africa.

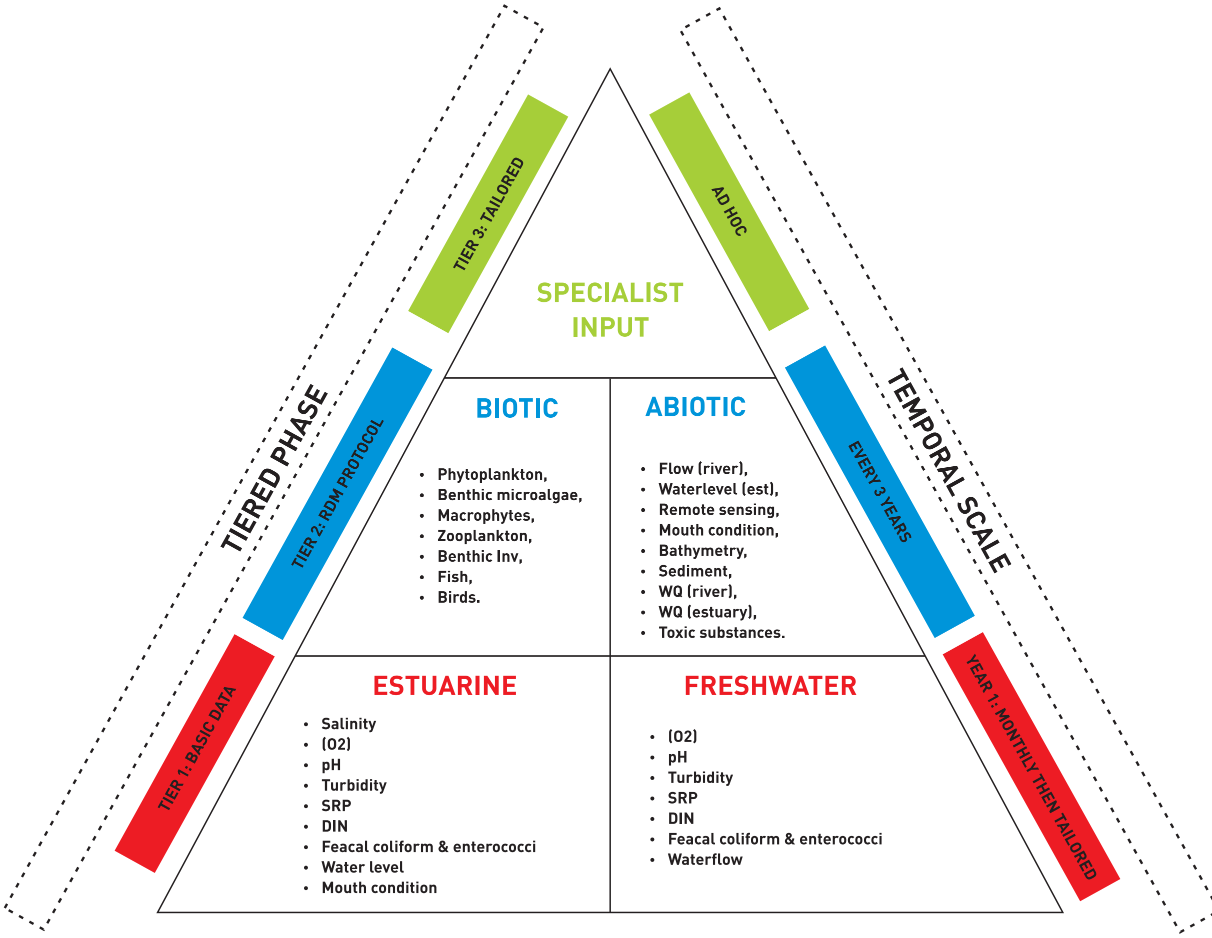


Figure 7. The National Estuarine Monitoring Programme for South Africa.

Figure 8. The Bloukrans Estuary is one of the estuaries for which Ecological Water Requirement studies have been completed. (Credit: NMMU/Water Wheel archives)

Estuarine resource use and quantification of benefits

Estuaries are subject to increasing pressure, both indirectly from the effects of catchment utilisation that affect their water supply, and directly from the increasingly large numbers of people who reside in or visit the coastal zone. Estuaries are productive systems that provide a valuable supply of goods and services, ranging from fisheries to recreational opportunities. Until the early 2000s, however, there had been no attempt to estimate the economic value of the ecosystem services provided by estuaries, with the result that their contribution to the national economy was under-appreciated. Recognizing the importance of quantifying the benefits estuaries provide to society a dedicated effort has been made to strengthen this field of interest over the past 20 years.

One of the most important values of estuarine systems is their contribution to fisheries. Resident fish populations are exploited directly in estuarine recreational and subsistence fisheries. But more importantly, estuaries provide nursery areas for numerous species of fishes that are exploited by recreational and commercial harvesting in the nearshore marine environment. These species are dependent on estuaries for the early stages of their growth. Lamberth and Turpie (2003)* showed that estuaries contribute a significant value to the economy in terms of both estuarine fisheries and their contribution to inshore marine fisheries, with the latter slightly exceeding the value realised within estuaries. In 2002, the total value of estuarine and estuary-dependent fisheries was estimated to be R1.3 billion. Although commercial catches are substantial both within estuaries and in the marine environment, it is recreational fishing activities that add the most value to the economy, with more than 20 times as many participants (about half a million vs under 23 000) as in commercial and subsistence activities and realising a value of more than 100 times greater per kg of fish caught. While subsistence fisheries are more localised, and involve smaller numbers of fishers these are important in the context of the livelihoods of the communities involved.

However, stock-assessments of key estuarine fish suggests that the current high level of estuarine fish production is probably not sustainable. Dwindling fish stocks are accompanied by lower catches, and the value realised from these fisheries. This has a much greater impact on commercial fisheries, upon which many people rely for their livelihoods, particularly in marine fisheries, than on recreational fisheries, which are less sensitive to catch returns. It was clear that sound management practices were needed to sustain caches in the future, as well as to ensure the conservation of estuarine biodiversity. The study showed that it makes good economic sense to remove commercial fisheries from estuaries, thereby halving the catch, but only reducing economic contribution by one percent. Commercial fishing in estuaries is predominantly gill-netting, mostly illicit, which is unselective, usually with a high by-catch of undersized and immature linefish and other species. By removing commercial fisheries, much greater recruitment of juveniles will be allowed into the sea. The study highlighted the fact that the most sensible overall policy would be to conserve estuarine stocks as nursery and source areas for marine fisheries. This is the most efficient option in terms of maximising resource productivity, economic benefits, and biodiversity conservation. In this manner resource productivity in both estuaries and the inshore marine environment can be enhanced by concentrating conservation efforts on estuarine stocks. Aside from ensuring ecosystem health and habitat integrity, stock status can best be improved by the reduction of catches. To minimise the cost of the latter, it should be targeted at fisheries that are either of low value per unit catch (e.g., estuarine commercial net fisheries) or fisheries whose value is not strongly affected by catch rates (i.e., the recreational fishery, which is much smaller in estuaries than on the open coast). Conserving estuary stocks requires the sound holistic management of estuaries, a spin-off being the improved conservation of all estuarine biodiversity.

Key outcome 6: An evaluation of the role of estuaries in South African fisheries highlighted their economic importance and resulted in management actions such as the nearly complete removal of commercial gill-nett fisheries from estuaries to restore their nursery function.

Figure 9. Eutrophic conditions, harmful algal blooms and fish kills affect the aesthetic and recreational value of estuaries which can reduce ecotourism opportunities. Here, algal blooms at Mhlangankhulu Estuary can be seen. (Credit: NMMU/Water Wheel archives)

Following on this, the valuation of changes in estuary services in South Africa as a result of changes in freshwater inflow become a core focus area. This led to investigations useful in guiding the efficient allocation of river water and to compare the value of the water abstracted and that of the flowing into the estuary (Hosking et al. 2004*; Hoskings 2010*; Adams et al 2010*; Bowd et al 2012*). Efforts were also made to investigate integrated ecological-economic modelling as an estuarine management tool using the East Kleinemonde Estuary as a case study (Turpie et al. 2009a*, 2009b*, 2009c*). Hoskings (2010)* showed that while many people had an interest in using estuaries, the primary demand was for the recreational services they yield. Surveys highlighted two main user populations of estuaries – people engaging in recreational activity and others engaging in subsistence activity. The former tended to be wealthy and the latter poor. The latter derived much of their value indirectly, by supplying services to those engaged in recreational activities. The collective response of the two populations typically yielded a skewed and bi-modal distribution of requirements. Demand for ecosystem services was found to positively correlate with location and the length of time an estuary mouth was open, but not with estuary conservation status. The opportunity cost of water flowing into an estuary increased according to the level of development in the region in which the estuary was located. The study concluded that the value of river inflow into estuaries is increased where a small change in flow causes a large change in the services the estuary yields, and where there are large numbers of users.

Restoration

Estuary restoration is the process of assisting the recovery of damaged, degraded or destroyed systems. Restoration frameworks usually consider: an assessment of the degraded site, identification of pressures, vision and restoration targets, plan for implementing and managing restoration interventions and a monitoring plan (Gann et al. 2019). Estuary health assessments completed for South African estuaries clearly indicate the areas where restorative action is needed. These mostly relate to reinstating and protecting freshwater inflows to estuaries, promoting sustainable resource use, and reducing developments in the EFZ (Estuary Functional Zone). Water pollution is also a major pressure on South African estuaries (Van Niekerk et al., 2019, Adams et al. 2020). Innovative approaches to restoring and improving water quality are necessary for conserving the country's estuaries and the benefits they provide to society. Various key interventions that can be used to improve estuarine water quality are currently being investigated using the urbanised Swartkops Estuary in the Eastern Cape as a study site.

Sustainable urban drainage systems (SUDs) that utilise biomimicry concepts have been installed at the Markman Canal to treat polluted stormwater from urban and industrial areas, and their efficacy is currently being monitored. Recently completed research (Wasserman 2021) has explored the potential of transforming abandoned saltpans into stormwater treatment ponds. It was determined that diverting stormwater into the saltpans will be a cost-effective approach to decreasing the high nutrient loads from the Motherwell Canal, which has been identified as a major source of pollution (Adams et al., 2019). In doing so, an important waterbird habitat that was lost when the saltpans were abandoned will also be restored, thus providing multiple benefits from a single restoration intervention. The roles of primary producers such as salt marsh, seagrass, and phytoplankton as nutrient and heavy metal filters are also being investigated. Lastly, a socio-ecological framework for restoring South Africa's estuaries has recently been developed and promotes greater collaboration across disciplines and institutions (Adams et al., 2020). WRC is investing in this research in line with the Society for Ecological Restoration's objectives and the UN Decade of Ecosystem Restoration (2021-2030). This research builds on an earlier study that investigated the response of blue carbon ecosystems to climate change (Adams et al. 2020*).

Key outcome 7: Past research has provided the knowledge for a national estuary restoration programme in line with the UN Decade of Ecosystem Restoration (2021 – 2030).

Conclusion

The WRC's contribution to estuarine research in support of effective policy development and resource management has been significant and lasting, through its financial contribution to research in environmental flow methodologies (under the NWA) to the development of key policies such as the National Estuarine Management Protocol (under the ICM Act). Health assessment tools developed as part of WRC studies have also become the backbone of national assessment such as the Estuaries Realm National Biodiversity Assessment, reporting on State of Environment, and SDGs.

In addition, the insights gleaned into the ecosystem function of large and small estuaries have contributed to South Africa's substantial knowledgebase on these important ecosystems and allowed us to participate and collaborate with the broader scientific community both in Africa and globally.

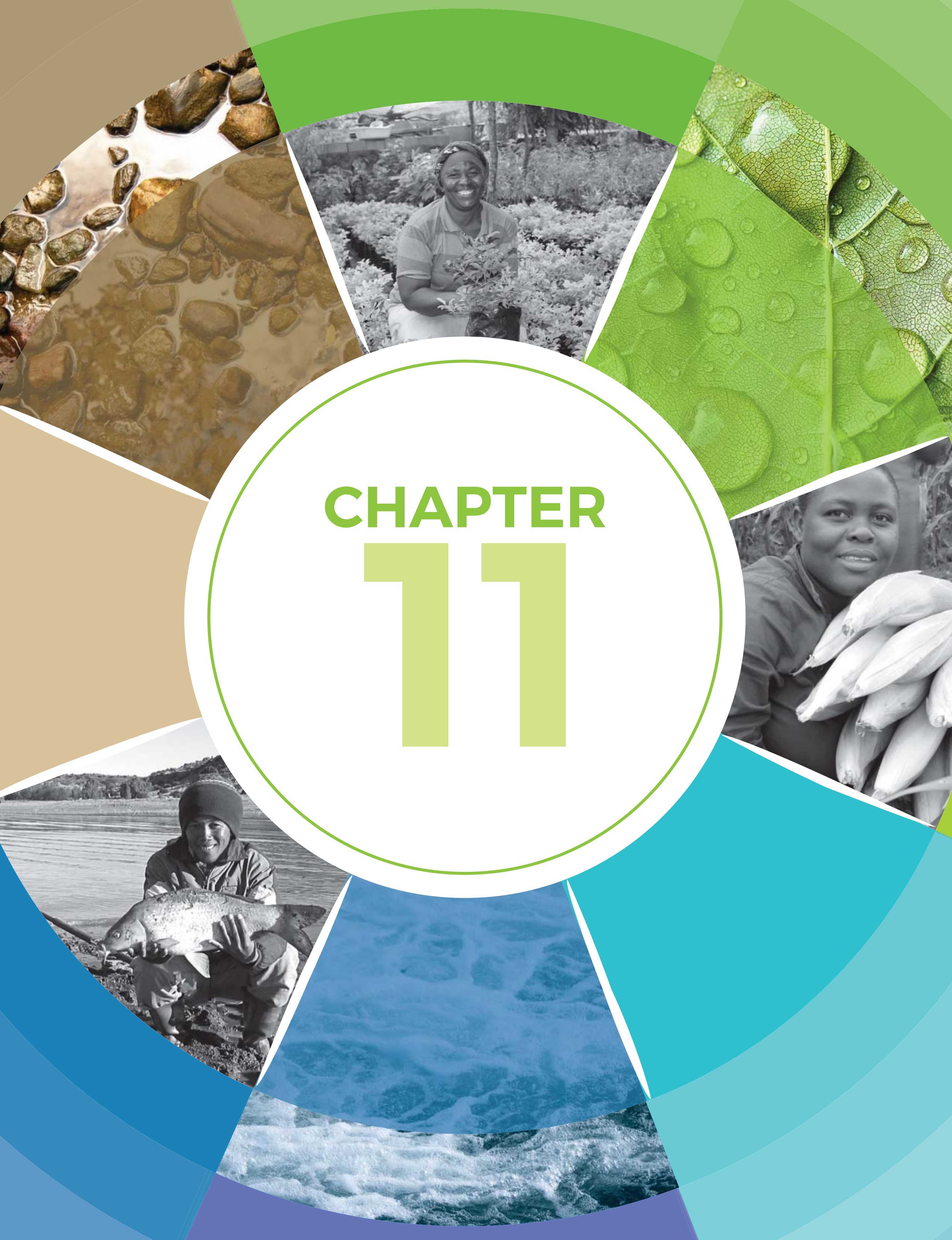
We would also be remiss if we do not acknowledge the multitude of students, funded under the auspices of the WRC programmes, who now hold prominent positions in academic institutes or government. Dedicated student funding has given us the ability to train and educate, in real-world settings, a host of students who have gone on to make their mark in this domain.

Supportive WRC steering committees that consist of both academic researchers and estuarine managers have also led to the development of a vibrant network of people involved in estuarine research and management.

Key future gaps are research into the impact of climate change, with special attention needed in the downscaling of climate change scenarios to real-world streamflow changes in estuaries as well as on ecosystem health and production in the adjacent marine environment. More research is also needed on the impact of hydrological or oceanic events on estuaries at regional scales, e.g., ecosystem responses to droughts or marine heatwaves. There is also a critical research gap in the understanding and predicting of change in sedimentary processes in relation to global change pressures, including the shifts this will cause in associated estuarine invertebrate populations. Restoration is an emerging research field, with the ever-changing, high-retention nature of estuaries requiring unique approaches to deal with this relative harsh environment. Action research is needed across a range of aspects to ensure an effective restoration toolbox is developed for estuaries moving forward, from habitat restoration, bank stabilisation, removal of alien species and improvement of water quality. There have been exciting developments in the monitoring of estuaries, from the use of high-resolution remote-sensing tools (e.g., Sentinel 2) on detecting change in mouth state and critical habitats, using machine learning in pattern detection and development of prediction models, to the use of eDNA to identify critical biodiversity. Soundscapes is also globally becoming an important monitoring tool in estuaries. There is also a need for interactive citizen science projects that can serve as an interface with civil society and assist with the collection of data on numerous aspects such as mouth state, alien species and fisheries catch data.

Figure 10. WRC project team and reference group for Nelson Mandela University research project on Response of Blue Carbon Ecosystems to Climate Change (photo credit: Janine Adams).

CHAPTER 11



SOCIO-ECONOMIC RESEARCH ON WATER IN SOUTH AFRICA: TRENDS, STRENGTHS, AND IMPACTS

Bongani Ncube, Maxwell Mudhara, and Lerato Phali

INTRODUCTION

The Water Research Commission (WRC) was established in 1971 as a body to generate new knowledge and to promote the country's water research. Over the years, not only has the institution funded and conducted groundbreaking research, but it has also contributed to the socio-economic issues facing the country, through innovation, intellectual capital, water-centred knowledge transfer, and application. In recent years, the WRC has implemented a paradigm shift to take research outputs into outcomes and impact for the broader society with a development focus towards accelerating solutions to the market and enhancing uptake (WRC Corporate Plan, 2018-2023). Through the partnership with the Department of Water and Sanitation (DWS), the WRC provides the sector with the knowledge and capacity to ensure sustainable management of water resources and enhance water services. This is done under both constitutional and legislative mandates including the Bill of Rights, the Water Research Act (Act No. 34 of 1971), the Water Services Act (Act No. 108 of 1997), and the National Water Act (Act No. 36 of 1998). In addition, the WRC has to align with policy mandates, such as those defined by the National Water Resource Strategy (2004, and 2013) and the National Development Plan 2030 (NDP 2030). The WRC also aligns with global mandates that South Africa is committed to.

In 2015, the United Nations (UN) General Assembly approved Agenda 2030 for Sustainable Development and its Sustainable Development Goals (SDGs), which has a vision of ending poverty and hunger, protecting the planet from degradation, ensuring prosperity for all, and fostering peaceful, just and inclusive societies. The WRC has contributed to South Africa's efforts in achieving the SDGs through funding research and innovations to address all the SDGs, particularly relating to SDGs 2 and 6. SDG 2, 'Zero hunger', is at the core of food security interventions, while SDG 6, 'Water and sanitation for all', relates to water and sanitation, which ultimately affects socio-economic facets of society (Cole et al., 2018).

Water is crucial for the general well-being of humans and ecosystems. It is an important input for agricultural production, and thus contributes to food security. Unfortunately, South Africa has been listed as a water-scarce country, where water insecurity has become a concern. There is an upward trend in the demand-supply gap, estimated to reach 17% by 2030 (Hedden and Cilliers, 2014). In addition, climate change exacerbates the situation, increasing the demand for irrigation. Irrigated agriculture contributes 40% of the total food production in the world, and is, on average, twice as productive as rainfed agriculture (Bonthuys, 2018). The increase in demand for irrigated agriculture has put pressure on water resources globally, and has thus put the management of water resources at the forefront of water research (Nyam et al., 2021). The WRC has played a key role in facilitating research on the management of water and water resources, such as improved water efficiency in agriculture, water use trade-offs, water governance and management. In support of government imperatives and policy, the research has focused on the sources, technology, beneficiaries, and institutions associated with water in the country (Akayombokwa et al., 2017).

The main objectives of the Water Services Act (1997) include the provision of the right of access to basic water supply, the right to basic sanitation necessary to secure sufficient water, and an environment not harmful to human health or well-being. The National Water Act (NWA, Act 38 of 1998) stipulates the efficient, sustainable, and beneficial use of water as key principles. Furthermore, the 2003 Strategic Framework for Water Services (SFWS), recognised that water use for small-scale agriculture is necessary for poverty reduction and the improvement of livelihoods. These policy instruments, in essence, show that water research should not only be focused on the technical aspects of water, but should also encompass socio-economic considerations.

The National Water Resource Strategy (NWRS, 2004) is the legal instrument for implementing or operationalising the NWA and is binding on all authorities and institutions implementing the Act (NWRS2, 2013). The strategic aims of the NRWS2 – protection, use, development, conservation, management, and control of South Africa's scarce water resources – resonate with the goals of the National Development Plan 2030 Vision. The NWRS2 aims to ensure that water serves as an enabler for inclusive economic and social development and not a hindrance. The first objective is to ensure that water supports the development and elimination of poverty and inequality, starting with the equitable and judicious management of the resource. This chapter, therefore, provides a review of the contribution of the WRC to socio-economic research, capacity building, development, and knowledge transfer in South Africa, particularly in the last two decades.

The earliest socio-economic study funded by WRC dates back to 1998. Bernhardt Dunstan & Associates carried out research on a project entitled the *Evaluation of on-site sanitation from a socio-economic perspective* (Report No. KV 114/98, 1998*). Since 2002, the organisation has been involved in water-related research that not only touches on technical aspects but is aimed at socio-economic improvement in South Africa and beyond. Various programmes and projects that have emanated from research funded or implemented by the WRC have provided communities with the opportunity to improve their livelihoods through training, capacity building and innovation. Some of the important projects that address the socio-economic sphere that the organisation has implemented over the years are discussed in this chapter.

Socio-economic projects funded by the WRC

Socio-economic topics funded by the WRC over the years include smallholder and commercial irrigation farming, domestic water use, food security, employment creation, and capacity building.

Smallholder irrigation farming

According to the most recent updates, the area under irrigated agriculture in South Africa is 1 334 562 ha (GrainSA, 2018). Despite its relatively small share of the agricultural sector, smallholder irrigation is deemed to be one way of uplifting rural communities (Sinyolo et al., 2014*; Fanadzo and Ncube, 2018*). Mainly located in rural areas, smallholder irrigation farming is attributed to farmers who extract water from smallholder irrigation schemes (SISs). SISs were established in the former homelands for occupation by black farmers in efforts to enhance agricultural production (Fanadzo and Ncube, 2018*). They have been identified as one of the key drivers of poverty alleviation in rural areas (Sinyolo et al. 2014*). Although smallholder irrigation is important for alleviating poverty and economic development in rural areas, the sector faces challenges related to water governance issues, lack of investment leading to dilapidated infrastructure, unreliable water supply, and distribution. Furthermore, farmers in the schemes lack access to credit, have inadequate extension services, lack entrepreneurial skills and access to markets. All these challenges hinder the ability of smallholder irrigators to sustainably improve their livelihoods and financial well-being (Maepa et al., 2014).

Figure 1. Farmers in smallholder irrigation schemes share the infrastructure but own individual plots where decision-making is heterogenous. (Credit: Maxwell Mudhara)

Commercial irrigation farming

Agriculture positively contributes to the national economy and food security, particularly through commercial irrigation schemes. Given that the land is getting drier due to climate change, there is a need to use resources for agricultural production more efficiently to promote long-term sustainability (Singels et al. 2018; Mettetal, 2019). Irrigation supports 25-30% of South Africa's national agricultural production and is used for producing about 90% of high-value crops (WRC, 2020). Commercial irrigation schemes were developed to support large-scale farmers and enable them to contribute to the food security of the country. Although the sector has been relatively successful over the past decades, the lack of maintenance and increasing costs of water extraction puts the profitability of commercial irrigation farming under pressure (Singels et al. 2018). There is also a need to continue with research to improve water-use efficiency.

Domestic vs agricultural water use

In recent years, South Africa has witnessed a growing number of protests related to the government's provision of services such as water and sanitation, which stimulated discussions about agricultural versus domestic water use (Tapela, 2013*). The agricultural sector contributes about 3% to the Gross Domestic Product (GDP) of the country although the sector uses about 60% of the available water supply (Water Information Network (WIN), 2014*; Brettenny and Sharp, 2016).

Urbanisation is contributing to increasing demand for water for domestic use, mining, and the industrial sector. This means that agricultural water users need to reduce the consumption of water and make it available for other uses (Smith, 2010). In 2001, the government introduced the idea of free basic water (FBW) which sought to provide citizens with free water, which amounts to 6kl per household per month. Before FBW, all household water usage needed to be paid for, provided it was supplied from a municipal source. The government introduced the FBW in efforts to improve public health, gender, and equity, to meet the constitutional rights of citizens to water (Smith, 2010). The increase in demand for water in other industries emphasizes the urgency to strive for sustainable management of water use. The emerging trade-offs in the alternative use of water have led to discussions on what is the fair and efficient allocation between agriculture and domestic use, or rural and urban use.

Figure 2. The WRC has supported several studies into the sustainability of free basic water, especially for informal settlements and rural areas. (Credit: 123RF stock photo)

Agriculture not only contributes to the country's economic development and supply of food products, but it also provides employment opportunities. As such, it is important to ensure adequate water supply in the sector. Often the challenges that government faces to ensure adequate water access for all sectors stems from institutional ineffectiveness, informal access to water (relating to illegal connections), and poor maintenance of infrastructure, which often leads to water scarcity in both urban and rural areas. It has been reported that social water scarcity, particularly in urban areas, is closely linked to livelihoods, whether the area is formal or informal, and even along racial divides (Tapela, 2012*). On the other hand, water insecurity in rural areas is often attributed to a lack of proper water management, poor management and maintenance of water resources, and weak local rules such as water scheduling (Mudhara and Senzanje, 2020*).

Food security

The achievement of food security is a key issue that the WRC has aimed to address for the past 30 years. Defined as the state of having reliable access to a sufficient quantity of affordable, nutritious food, statistics reveal that about 20% of South African households were food insecure in 2017. Additionally, there seems to be a divergence in the economic growth path and its overall poverty and inequality reduction, which consequently, has not yielded pro-poor growth (Bhorat and Kimani, 2018*). Ensuring household food security and reducing poverty are important policy goals that the government has aimed to achieve through welfare assistance such as grants and feeding schemes in schools. However, food affordability remains a problem for many households, preventing them from accessing nutritious and adequate food. In rural areas, factors such as higher transaction costs arising from high transportation costs of food, and the population spending a large proportion of their incomes on food, leave them trapped in food insecurity (Misselhorn and Hendriks, 2017). About 18% of households can potentially grow food in homestead backyard gardens in rural villages. The achievement of food security using a diminishing water resource requires its efficient and sustainable utilisation and management, which has been the focus of the WRC in the past years (Wenhold et al., 2007; Backeberg and Sanewe, 2011; Chitja and Botha, 2020*).

To improve food security by ensuring that school children have access to adequate nutritious food to eat daily, the WRC embarked on a project of establishing food gardens. School food gardens are important because they can teach learners about gardening concepts and skills to increase home production for household food and nutrition security. The food gardens were established in the Mamelodi, Pretoria area in two schools, namely Bula Dikgoro and Mahlasedi Masana Primary School (Araya et al., 2020*). The gardens provided vegetables to supplement nutrition for children and adults in the community, improved the schools' infrastructure required for crop production and contributed to human capacity development through school engagement and on-site training to transfer skills to the communities. The project involved providing Agricultural Sector Education and Training Authority (AgriSETA) accredited training to educators and garden personnel on methods of crop production (Araya et al., 2020*). The WRC has since then implemented and assessed the impact of food gardens in various communities (Mnkeni et al., (2006); Stimie et al., 2010*; Araya et al., 2020*).

Figure 3. Female farmers dominate as smallholder irrigators and provide for their household food security. (Credit: Maxwell Mudhara).

Unemployment

In South Africa, the broad unemployment rate is 37% and the Gini index of income inequality is 0.65, making it one of the most unequal societies in the world (Cole et al. 2018). The persisting high rates of unemployment in the country are said to be due to various factors. A commonly highlighted factor for high unemployment is the legacy of apartheid, which entailed poor education and training, as most black people were excluded from the educational and formal employment opportunities. The mismatch in labour supply and demand has also contributed to the high unemployment rates as the number of job seekers far exceeds the number of vacancies available, particularly in the formal economic sector. The high search costs also discourage job seekers, with evidence indicating that black and coloured job seekers are likely to remain searching for longer than their white or Indian counterparts (Banerjee et al, 2008; Pasara and Garidzirai, 2020). The unemployment rates can also be attributed to global economic conditions, while structural factors resulting in lengthy times spent in unemployment have contributed to the persistence of unemployment (Nonyana and Njuho, 2018).

These are pressing socio-economic issues that impact the development of the country. The WRC has addressed some of the issues over the past years through the development of appropriate interventions in the water sector.

In light of the high unemployment rate in South Africa, the WRC partnered with the Department of Science and Innovation to implement the Water Graduate Employment Programme (Water GEP) which sought to assign 400 unemployed graduates who can contribute towards the water and sanitation sector over three months (January 2021 to end March 2021). The Water GEP seeks to enhance sustainable economic development through job creation in academia, small, medium, and micro enterprises (SMMEs), industry, and water-service institutions. The project matches graduates in the water sector with institutions based on their qualifications and needs. The project is funded through AfriAlliance who received funding from the European Union's Horizon 2020 research and innovation programme. The project has potential long-lasting effects due to the experience the students will receive, the likelihood of being absorbed into the institution after the pilot, the general exposure the graduate receives, as well as the opportunity to be economically active in a society ridden with high unemployment rates. The WRC has conducted various research projects relating to the socio-economic issues highlighted in the preceding sections (WRC, 2021).

History of WRC involvement in addressing socio-economic issues in the last 20 years

The WRC has contributed immensely to society through projects implemented in various fields. Some of the key projects that the WRC has initiated, funded, and managed in the socio-economic sector for the last twenty years are listed in Appendix 1. The listed research projects focused on food security, welfare, governance, water scarcity and livelihoods strategies. Although there are numerous projects the WRC has undertaken, this chapter highlights four case studies that contributed to various socio-economic issues in the past 20 years.

Smallholder irrigation and agricultural development

The WRC has supported projects that sought to contribute to rural poverty alleviation by improving the productivity and profitability, gender equity and environmental sustainability of smallholder irrigation. For example, Machete et al. (2004) assessed the productivity and profitability of smallholder irrigation and their potential contribution to food security and poverty alleviation. The study found that agricultural productivity in the irrigation schemes was low. Several factors affected productivity, e.g., infrastructure maintenance, poorly trained extension agents, and limited access to irrigation water (due to inequitable use) and weak institutional arrangements, including poor participation of irrigators in scheme management. Fanadzo and Ncube (2018*) and Mudhara and Senzanje (2020*) conducted more recent WRS-funded studies and found similar results to those of Machete et al. (2004). The studies have recommended that farmers be trained in water management and irrigation scheduling, while the gender gap in participation in irrigation water management needs to be narrowed, and that the irrigation management transfer be structured to be more inclusive of farmers.

Figure 4. The WRC has supported several projects to improve the productivity of smallholder irrigation schemes. (Credit: WRC archives)

Empowerment of women, water and land use security, and generation of knowledge

For years, most studies dealing with socio-economic issues focused on productivity, water use and scarcity, and food security, without exclusively evaluating the trends for female farmers. Studies have shown that the majority of farmers in rural areas in general, and smallholder irrigation schemes in particular, are women (Sinyolo et al. 2014*; Chitja et al. 2016*; Mudhara and Senzanje, 2020*). In response to persisting problems of high levels of poverty, inequality, low wage employment, underdeveloped infrastructure, weak market linkages, conflicted land institutions, high transaction costs, and lack of human capital in rural areas, which affect women in rural areas, three WRC funded research projects on empowerment of women were conducted (Denison et al. 2015*; Chitja et al. 2016*, Oladele, 2016*). The studies were conducted across four provinces, i.e., Eastern Cape, KwaZulu-Natal, Limpopo, and North West (Denison et al. 2015*; Chitja et al. 2016*, Oladele, 2016*). The studies investigated the constraints, opportunities, and challenges undermining the empowerment of women and their achievement of sustainable rural livelihoods. The three studies suggested the need to be cognisant of the women's circumstances in terms of literacy levels, appropriate training techniques, and the need for multi-stakeholder dialogue inclusive of rural women. They also highlight the need for appropriately designed government programmes and extension approaches, which will meet the needs of rural women, policy awareness, training on market access, and institutional development.

Denison et al. (2015*) explored the empowerment of women through water use security, land use security and knowledge generation for improved household food security and sustainable livelihoods in selected areas of the Eastern Cape. The importance of this project stems from its focus on female farmers, and also on its consideration of sustainable livelihoods, which ensure that poverty alleviation is not short-lived. The study found that about 70-94% of the households had insufficient food, and that food insecurity was prevalent. Women in the area faced the triple burden of reproductive work, productive work, and community roles, and yet their asset ownership was low. This translates to women not having enough time to expand their agricultural activities. The study found an inactive land market and that water resources in the villages were below prescribed levels. Furthermore, the farmers lacked technical aspects such as water storage, financial management, knowledge of marketing contracts and pricing and costing. The study identified eight intervention strategies to improve food security, mitigate the effects of water insecurity, balance domestic vs agricultural water use, as well as knowledge transfer in the villages. These included the initiation of agricultural learning through knowledge networks for all food growers and farmers; the development of homestead multiple-use storage systems; the establishment and application of water harvesting and conservation methods; linking farmers to the commercial seedling nursery or establishing a local nursery; financing and training of mechanisation contractors; establishment of a local land administration system; value-chain mapping and optimisation for farmers; and awareness of available financial services and commercial partnerships.

Figure 5. The study of Denison et al (2015) aimed to ensure a comprehensive understanding of the constraints, challenges, opportunities and interventions required for the empowerment of women to promote household food security and rural livelihoods through increased water productivity. (Credit: Umhlaba Consulting/Water Wheel archives)

Environmental awareness and livelihoods

In order to address socio-economic, community and environmental issues, the WRC adopted a holistic approach in implementing the Wise Wayz Water Care Project (Davids et al., 2021). The project ensured that community members in the Mbokodweni and Folweni catchments in KwaZulu-Natal took ownership of restoring ecosystem health and improving their livelihoods. The project, which was initiated in 2016, with a mission of "one river, one team, one mission" involved the communities working with each other to remove alien invasive plants, infrastructure monitoring and evaluation, and the development of recycling buy-back centres, which generated incomes for the participants. The communities also established food gardens which had the potential of being up-scaled to commercial agricultural enterprises. For capacity building, the participants received training in solid waste removal from watercourses, as well as safety health & environment. This project not only contributes to the economic welfare of the communities but also their environmental health.

Entrepreneurial development pathways for homestead food gardening

Several challenges in smallholder irrigation farming prevent farmers from transitioning from subsistence, and or small-scale farming to commercial farming. These include lack of market access and human capital, resource constraints, and transaction cost (Mudhara and Senzanje, 2020*). However, there might be limitations that farmers place upon themselves, particularly if they lack psychological capital, which not only prevents them from expanding their farming enterprises but also limits their potential to create employment and maintain sustainable livelihoods (Wale and Chipfupa, 2018). There is great potential to create employment in rural areas through irrigation farming (Sinyolo et al. 2014), provided that the right development pathways are undertaken. To this extent, Wale and Chipfupa (2018) undertook a project to assess appropriate entrepreneurial development paths for homestead food gardening and smallholder irrigation crop farming in the KwaZulu-Natal Province.

The study aimed to bridge the knowledge gap in terms of entrepreneurship in SIS. Its importance stems from considering a dimension that is often overlooked in agriculture, and which can potentially directly create employment opportunities and boost local economic development in rural areas. The study was carried out in four irrigation schemes in the KwaZulu-Natal Province and evaluated development paths for expansion from homestead food gardening to smallholder irrigation farming. The researchers further outlined the appropriate development paths for establishing sustainable farming businesses. The study found that not all smallholder farmers aspired to expand their enterprises, and therefore no one-size-fits-all approach should be taken in developing pathways. The study suggested that diversity and heterogeneity should be reflected in the different strategies and policies to support smallholder farming. The study also recommended a skills training development programme, which would focus on agricultural production, irrigation water management, and business and entrepreneurial skills. Additionally, the establishment of a marketing strategy to enhance market participation could help business-minded small-scale farmers expand. Such market strategies could involve market transport systems as transport was identified as one of the main challenges the farmers face. It also highlighted the concept of 'buddy farmers', which promotes peer farmer support. This would be immensely beneficial if pairing is facilitated between entrepreneurial farmers and those who lack the necessary skills.

These case studies show how WRC-funded projects have contributed to the socio-economic dimensions in the past 20 years. Although some challenges persist in the socio-economic sphere, there have been great strides in the impact of the contributions the WRC has made over the years. WRC-funded projects have also shaped our current understanding through innovations that have improved the lives in communities.

Governance of irrigated water

Since water is a scarce resource, determining mechanisms for sharing is critical. The WRC has supported work that has sought to understand and develop sustainable mechanisms of water allocation. For example, Breen et al. (2004) conducted a study on how socio-economic and cultural values affect resource use. Mazibuko and Pegram (2006*) looked at how cooperative governance could be achieved between catchment management agencies and local government. The issue of water user associations (WUA) as instruments of enabling equitable water allocation has been topical in South Africa for a long time. WRC has invested resources into understanding the required structural configuration of WUAs and also further studies on factors determining their performance. For example, Burt et al. (2007*) and Auerbach (2011*) looked at the roles of WUA as local institutions for water governance. In a similar line of thought, several studies looked at women's empowerment as one way of ensuring gender balance in water management and access (Denison et al. 2012*; Oladele and Mudhara, 2016*; Chitja et al., 2016*). Lastly, some studies have directly looked at the governance of water, e.g., Ncube and Lagardian (2018*) and Mudhara and Senzanje (2020*). Nevertheless, these studies have raised further questions regarding the complexity of the water sharing mechanisms. Specifically, Mudhara and Senzanje (2020*) pointed to the plurality of rules and regulations that the irrigators have to contend with and point to the need for further studies on how these rules and regulations can be integrated to enhance the socio-economic outcomes from irrigated water.

Figure 6. An academic visit to the Lower Olifants River irrigation scheme, in the Western Cape in 2010. (Credit: Lani van Vuuren)

How WRC funded projects have shaped current understanding through innovations and interventions

The WRC has contributed to society through innovations and projects that have shaped the understanding of rural systems, and which has helped communities make better use of their limited resources, in a sustainable manner. Below, a few of the innovations or interventions are highlighted, with the focus on what and how they benefited the communities.

Rainwater harvesting

After many years of investment in research into rainwater harvesting and soil water management, a number of innovations have successfully been developed and applied. These include capacity building through the development of training and extension manuals (Sanewe and Backeberg, 2012). Rainwater harvesting (RWH) is the process of collecting and concentrating rainfall as runoff over from a larger area, for the productive use of the water.

Figure 7. The WRC has funded the development of a range of tools and guidelines for the implementation of rainwater harvesting.

The WRC went through phases of initiation (1995–2007) and consolidation (2008-2011) in RWH research. The period 2009–2019 was the expansion phase (Sanewe and Backeberg, 2012), with a strategy for achieving effective knowledge dissemination and practical training to encourage productive rainwater use for food crop production, commencing in 2013. The strategy was to focus on knowledge dissemination and training for skills development of water use in homestead gardening, and rainwater harvesting for cropland food production. In-field rainwater harvesting promotes run-off between crop rows in agricultural plots. It is a good conservation agriculture tool as it combines the advantages of water harvesting, no-till, basin tillage, and mulching. It is thus a risk-free, socially acceptable technique that combines rainwater harvesting and conservation techniques to increase crop yields. Monde et al (2012*) highlight that the method is economically affordable and poses minimal damage to resources. It, therefore, provides an agronomically, environmentally, and economically sustainable way to plant crops.

Multiple-use water services

The WRC, in collaboration with the African Water Facility of the African Development Bank, co-founded a project entitled 'Operationalising community-led multiple-use water services (MUS) in South Africa' (van Koppen et al., 2020***)*.** The project, which ran from 2016 to 2020, applied a community-led infrastructure design and construction process in six diverse villages in Sekhukhune and Vhembe, two of the poorest districts in the Limpopo Province. The project addressed the growing problem of maintenance backlogs and the need for support to self-supply, in particular, through 'small investments for high benefits. The project developed ownership in the community and improved technical and institutional capacities for future operation and maintenance of the infrastructure (van Koppen et al., 2020).

Reuse of greywater

Greywater is a term often used to describe sullage, which is water from household showers and baths, and washing machines, but not from the toilet (Nel et al. 2017*). It is a potential source of nutrients for plant growth, which can be beneficial to households that cannot afford fertilizer. The soapy nature of greywater may act as pest repellent under some conditions, overall making it economically sustainable (Nel et al. 2017*). Due to the limited supply of water, reuse becomes important to relieve pressure on the available water supply. The WRC has conducted research on greywater for household agricultural production (Carden et al. 2007*), with evidence showing that it is a sustainable way to use water in both urban and rural settings.

Community and school food gardens

Promoting food security is a key mandate of the WRC, hence its involvement in research focused on funding the establishment and impact of community and school food gardens (Araya et al., 2020*). The gardens are established in vulnerable areas such as poor communities or schools. They are seen as a tool to enhance the nutritional status of beneficiaries and can impact their health. The gardens also have the potential to change eating behaviours and are useful in spreading knowledge and skills for food production. Furthermore, the gardens supplement school feeding schemes, ensuring that children consume healthy diets from an early age. They also contribute to teaching learners about gardening concepts and skills, with the hope that learners can use their skills to establish gardens in their own homes.

Best management practices

Several guidelines on best agricultural management practices to enhance livelihoods have been released by the WRC over the years (Mnkeni et al, 2010*; Tshuma and Monde, 2012*; Van Averbeke, 2019*). For irrigated agriculture to be sustainable and improve livelihoods, various skills and knowledge are needed. A farmer needs technical production skills, business acumen, water and water resource management, and exposure and the ability to assimilate new knowledge. If there is a shortage in any of the above-mentioned, then optimal performance is not guaranteed. As such, the best management practices that have been formulated through research by the WRC, provide guidelines to how farmers can utilise their resources and skills to yield better productivity results, to improve their livelihoods (Mnkeni et al. 2010*). All these interventions contribute to better productivity and economically viable ways of utilising resources. As such, they can contribute to household food security, poverty alleviation, and improve the socio-economic status of farmers. In addition to these innovations, the WRC has contributed to society through its mandate of capacity building.

Market access

Market access plays a critical role in allowing smallholder irrigation farmers to sustain their livelihoods. Poor access to markets is often given as one of the reasons for the poor performance of smallholder irrigation schemes. A number of WRC-funded studies have looked at markets in one form or another. For example, Jordaan and Grove (2012*) looked at the contribution of water use to value chains in agriculture. Among other things, and in agreement with many other studies, they recommended that smallholder producers have to grade their produce so that they are attractive to traders and fetch better prices. Oladele and Mudhara (2016*) identified various areas in which women farmers could enhance their farming practices and also their participation in the markets. Similarly, Oladele and Mudhara (2016*) recommended the mentorship of women to understand and participate in the agricultural value chain.

Capacity building

Capacity building is understood to be conditional upon improving knowledge and changing people's behaviour so that they can make more informed decisions, adapt better to changing conditions and be more effective in carrying out decisions (Breen et al. 2004). In the South African context, it involves providing opportunities, particularly to the previously disadvantaged, for addressing past inequities. The WRC as an organisation is involved in capacity building, from funding postgraduate students to empowering communities and individuals across the water sector.

The WRC set up the Research Partnership Fund to promote research capacity building at historically disadvantaged universities. It has further made it an obligation for researchers to address capacity-building in their research proposals. The capacity building could be in the form of funding postgraduate students to work on the research topic, or workshops in the communities the research is focused on. Added to this, the funded organisations have released training manuals for extension workers, farmer co-operatives, universities, farmers, and civil society. These include training on natural resource management, water management, agricultural productivity, water use efficiency, smart agriculture, and climate change adaptation. Wise Wayz Water Care Project (Davids et al., 2021) and the community and school food gardens (Araya et al., 2020*) are also part of capacity-building efforts.

Local, national, and global applicability of the outcomes of WRC projects

The outcomes of projects undertaken through the WRC are important due to their applicability to other parts of the continent, and the global south, in general. South Africa is a developing country, with many characteristics of a developed economy. However, dynamics found in its agriculture, irrigation, particularly smallholder management, production, and role players, are very similar to those of other developing countries. Mabhaudhi et al. (2019) applied an analytical model of the water-energy-food (WEF) nexus to assess rural livelihoods in southern Africa. The results showed that development outcomes such as improved livelihoods, enhanced water and food security should not be targeted in isolation. The WEF nexus is a framework that can be applied in most countries in Africa to improve the livelihoods of vulnerable groups and identify priority areas for intervention. And as such, can be applied in other regions to target developmental goals.

Figure 8. A schematic representation of the water-energy-food nexus

Gender disparities in the management of communal resources such as irrigation schemes do not apply to South Africa alone. Due to the traditional roles that women are assigned across the continent, it becomes challenging for them to participate in the management of resources, despite being the primary users. The WRC has funded research on the governance of water resources, which has identified and recommended the need for women empowerment and participation (Mudhara and Senzanje, 2020). These outcomes can be applied in other countries where women are marginalised and do not have a voice. Through the research, South Africa can set the tone on how sustainable and inclusive resource management can improve the livelihoods of the parties involved. Similarly, interventions such as food gardens can help improve food security in poverty-stricken regions, as the collective action, with the same purpose, can yield better outcomes for all involved.

Future research

There is a need to assess institutional actors' interaction within communities to help develop linkages and synergies that will enable sustainable use of water resources, improve farmer performance and productivity, and alleviate poverty.

Further research to enhance the understanding of how the use of water for agricultural purposes contributes to local development is needed. This research will allow the government to accord the commensurate resources to the improvement of the water sector. Although most small-scale farmers do not have access to formal markets, some of their produce still ends up in the hands of consumers. As such, there is a need to evaluate how far the economic benefits of water contributes to the community level value chains. To enhance livelihoods in predominantly agricultural communities, secondary production and services should be explored. A research gap exists in the establishment of secondary production opportunities that non-primary producers can participate in to enhance local economic development. This includes the establishment and development of marketing groups, agro-processing traders, and entrepreneurs. However, unpacking how smallholder irrigators could enhance their value chain participation remains an area requiring further enquiry.

The WEF nexus is an internationally emerging study area that incorporates water into joint use with energy for food production. The WRC should place resources into further exploration and applicability of this new area at all levels.

Climate change is set to have a greater impact on water availability, agricultural productivity, and ultimately socio-economic outcomes, particularly livelihoods and welfare. Research on the effects at farm level is required. Other chapters in this book have recommended mitigations and adaptation mechanisms for addressing the climate change challenge.

While several studies have looked at water governance and water allocation mechanisms, rules and regulations, there remains room for exploring this subject further in order to enhance equity and productivity. There is a need for further research to enable access to productive water for the poor and marginalised. Current efforts in hybrid water legislation are commendable, but there is a need to speed up the research and the processes, especially around the transformation of irrigation boards into water user associations. Further research on how water is managed at local up to the national level and the linkages thereof are required, with a view of achieving harmony and enhance outcomes for everyone.

Summary

Socio-economic issues are important as they essentially represent the backbone of society. For the last 25 years or so, the WRC has contributed immensely to socio-economic aspects of water in the country. Aligning itself with government imperatives, the organisation has contributed to the areas of food security, sustainable water use, social welfare, economics, and agricultural productivity. This chapter provided insight on the facets the WRC focused on through research and outlining key projects that have contributed to solving socio-economic problems in the country. It further highlights the innovative solutions championed by the organisation, which have improved local communities over the years, as well as highlighting how the research outcomes can be applied in other regions. The work conducted over the years indeed shows that the WRC has stuck to one of its key goals of contributing to livelihoods in South Africa, and beyond.

Appendix 1: Water Research Commission-funded socio-economic research projects

ISBN Number	Authors	Project title	Year
1-86845-424-X	Dunstan B and associates	Evaluation of on-site sanitation from a socio-economic perspective	1998
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1-77005-376-X Set 1-77005-373-5	F Reinders; M de Lange; M Botha; J Adendorf; CM Stimie; C du Plessis; U Moodie	Revitalisation of smallholder rain-fed and irrigated agriculture: A guide for farmer trainers and facilitators: Training Tool: Part 3	2005

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1-77005-438-3 Set 1-77005-436-7	Pegram G; Mazibuko G	Guide for local government cooperation with catchment management agencies	2006
1-77005-439-1 Set 1-77005-436-7	Pegram G, Mazibuko G	Guide for catchment management agency cooperation with local government	2006
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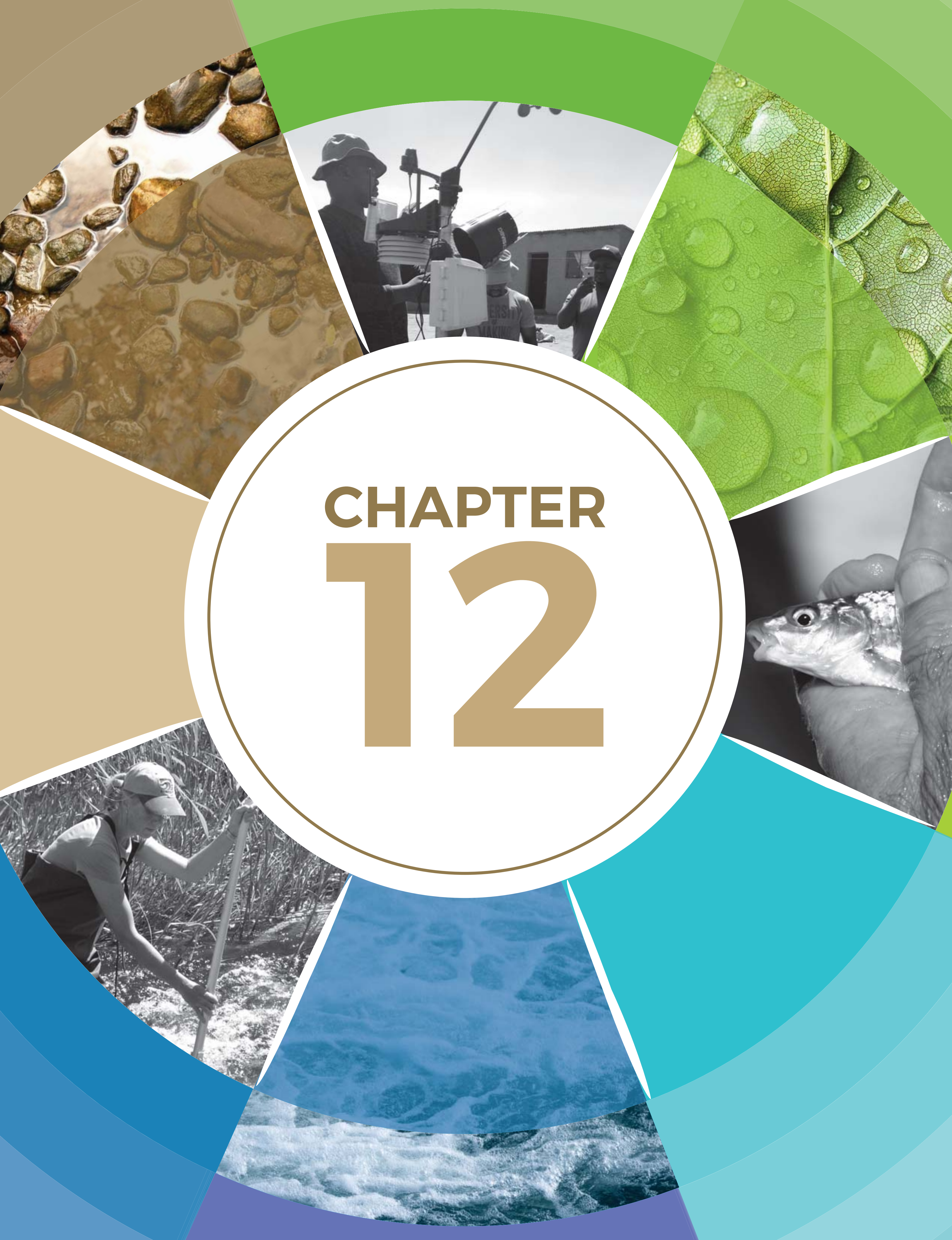


CHAPTER 12

CLIMATE CHANGE: ABIOTIC DRIVERS, IMPACT ON WATER RESOURCES AND ECOSYSTEMS, MITIGATION, AND MANAGEMENT OPTIONS

Helen Dallas, Nick Rivers-Moore and Mohammed Kajee

INTRODUCTION

"Take urgent action to combat climate change and its impacts" – this is the Sustainable Development Goal (SDG) 13 'Climate Action' of the 2030 Agenda (United Nations, 2018).

In 2002, the Water Research Commission (WRC) commenced a comprehensive research programme on climate-change impacts on water resources. This programme relied heavily on WRC water-related research on climate, atmosphere, ocean-atmosphere and hydrological modelling undertaken during the preceding 15 years. Later, the WRC produced the 'Research Portfolio on Climate Change for 2008-2013', a culmination of a discussion paper on current climate change research efforts in South Africa in relation to water, the national policy environment, and a national workshop (Green, 2008*). In this, priority topics and potential initiatives requiring water-sector participation were identified, including 1) refinement and communication of climate-change scenarios, projections, information, and data; 2) identification and quantification of impacts on water resources, including ecosystems and water quality; and 3) development and implementation of adaptation strategies and mitigation measures.

These topics later became themes in the Climate Change Lighthouse, namely impacts of, adaptations to and mitigation options regarding climate change (WRC, 2018) and have formed the recent focus of the WRC's strategy with respect to climate change in South Africa. Climate change research is relevant within all the WRC's key strategic areas, including Water Resources and Ecosystems, Water Utilisation in Agriculture, and Water Use and Waste Management; and climate change impacts ecosystems; agriculture, urban and industrial development, while its consequences have social and economic impacts.

South Africa is a water-stressed country with a mean annual precipitation (MAP) of 500 mm per annum (approximately 60% of the world average) (Zucchini and Nenadić, 2006). Climate changes include shifts in mean condition, variance and frequency of extremes of climatic variables, which result in changes in water quantity, especially in arid and semi-arid regions (Schulze, 2011*). Hydrologically, South Africa has a high-risk climate with very high year-to-year variability (e.g. a 10% change in rainfall can result in up to a 20–30% change in runoff) and a low conversion of rainfall to runoff (Stuart-Hill et al., 2011*). Runoff response to rainfall is also non-linear, with a larger proportion of rainfall being converted to runoff when a catchment is wetter, either because a region is in a high rainfall zone or because the soil water content is high as a result of previous rainfall (Schulze, 2011*). More than 50% of the water management areas in South Africa are currently in deficit, based on the ratio of annual withdrawals-to-availability (Alcamo et al., 2002), with southern Africa a 'critical region' of water stress (Alcamo and Henrichs, 2002). The ratio between MAP and mean annual potential evaporation is one way to quantify the relative dryness of the region, which varies from 1 in the east to >10 in the arid west (Schulze, 2011*). According to Kundzewicz et al. (2007), southern Africa is on a negative trajectory of climate-related changes, with precipitation, humidity and runoff decreasing, while the intensity and, in some case, frequency of droughts is increasing. The emphasis on climate related research, and the inclusion of climate change as one the WRC's lighthouses, is thus highly appropriate.

This chapter provides an overview of research related to climate change previously funded by the WRC. It focuses on Water Resources and Ecosystems, with specific focus on freshwater and, in particular, riverine, ecosystems. We discuss research on abiotic drivers of climate change, in particular climate-change-relevant research on precipitation, air temperature and evaporation in South Africa, and the development of climate change models for predicting trends in these drivers. We discuss research on the consequences of climate change on freshwater ecosystems, including those affecting water quantity, water quality, physical habitat and biological assemblages. Managing and mitigating the impacts of climate change are discussed and protocols and tools for managing water temperature in river ecosystems are provided.

Abiotic drivers of climate change

The primary drivers of climate change are changes in precipitation (areal or orographic rainfall; for example, changes in temporal or spatial patterns), shifts in precipitation patterns, increase in ambient air temperature, and increase in evaporation. Secondary impacts include an increase in the frequency of flooding and droughts, increase in sea-levels, and biological responses to the impacts of climate change (Green, 2008*).

Precipitation, air temperature and evaporation in South Africa

Rainfall and air temperature are the two elements of climate most important in determining the diversity and abundance of fauna and flora as well as a whole host of anthropogenic activities, including human settlement, economic development, and agriculture (McNeill et al., 1994*). As such, understanding how rainfall and temperature patterns have changed, are changing and will change under future climate change scenarios is imperative not only for human survival, but also for the survival of the diverse life forms that inhabit the planet. WRC-funded research on precipitation and air temperature in South Africa within the WRC dates back to the late 1980s, with studies focusing primarily on mapping mean annual rainfall statistics for the country (Dent et al., 1989*; Seed, 1992*; Mather et al., 1997*). The first WRC project on modelling present-day climatic conditions for southern Africa focussed on developing a stochastic model for multiple climate variables (including temperature) at specific sites across South Africa (Brandao and Zucchini, 1990*). Following on from this, McNeill et al. (1994*) described a daily rainfall model for South Africa, which was calibrated at 2 550 sites across the country and captures all probalistic properties of the daily rainfall process at these sites. Jury et al. (1996*) identified mechanisms that govern in-season (15-40 day) variability of summer convection over the plateau of South Africa and its adjacent ocean areas, noting that in-season oscillations of rainfall are of significant amplitude over South Africa; while Jury (2002*) developed a statistical system to forecast summer rainfall over South Africa.

Daily and monthly rainfall datasets were consolidated and administered by the Computing Centre for Water Research early in 2000 and were a valuable resource for future studies. These rainfall datasets, together with data from the South African Weather Service, the Agricultural Research Council, the South African Sugar Association, and a large number of municipalities, private companies, and individuals; were used to develop a raster database of annual, monthly and daily rainfall for Southern Africa (Lynch, 2004*). This database consists of more than 300 million rainfall values for approximately 14 000 stations. Subsequent to these studies, a number of projects modelled various aspects of rainfall in South Africa, including extreme rainfall events (Joubert et al., 1999*; Smithers and Schulze, 2000a*; Lennard et al., 2013*), flood estimation (Smithers and Schulze, 2003*) and spatial interpolation and mapping of rainfall (Smithers and Schulze, 2000b*; Clothier and Pegram, 2002*; Pegram, 2003*; Schulze and Maharaj, 2004*; Pegram et al., 2005*).

In terms of air temperature mapping, Schulze and Maharaj (2004*) completed an important project that developed a gridded daily temperature database for South Africa, using methods to infill missing daily maximum and minimum temperature values for South Africa between 1950 and 1990. This database was one of South Africa's first comprehensive temperature time-series databases and acted as a data source for future projects as well as providing considerable methodological progress in dealing with and handling temperature time-series data (Schulze and Maharaj, 2004*; Schulze, 2011*; Dallas and Rivers-Moore, 2019a*, b*). Although freely-accessible South African rainfall and air temperature databases have excellent records from 1950 to 1999, most of the measurable climate change impacts have occurred in the past 20 years. While the abovementioned studies were not directly focused on precipitation and temperature as they relate to climate change, they were a valuable first step and formed the basis upon which several studies could assess long-term changes to South Africa's rainfall and temperature conditions and make projections for these variables into the future.

Limited projects have dealt with how climate change may affect evaporation rates in South Africa, providing scope for future research on this important component of the climatic system. The capacity for this already exists, through existing frameworks such as the Köppen climate classification for South Africa, which exists for both current and future climate conditions. To date only two studies have assessed evaporation rates across large parts of South Africa, although these are not in relation to climate change. McKenzie and Craig (1999*) developed methods for upscaling pan measurements to evaporation losses from rivers in the Orange River basin while Everson (1999*) sought to determine the evaporation rate from flowing water along the Orange River and to compare these results with pan evaporation data. This study importantly demonstrated that evaporation rates for entire river systems can be modelled using standard weather station and flow data (Everson, 1999). Beyond this, there are limited projects that have dealt with how climate change may impact evaporation in South Africa, providing scope for future research to focus on this important component of the climatic system.

Figure 1. The Orange River. (Credit: 123RF stock photo)

Climate change models for predicting trends

According to Ziervogel et al. (2014), South Africa arguably has the most advanced research, observation, and climate modelling program on the African continent, with expertise situated across several universities and science councils, and several South African researchers leading and participating in international global-change research programs. Climate-change modelling is a complex topic so in this chapter we provide only some highlights. Global and regional climate change models predict likely trends in the magnitude and amplitude of event-driven systems, primarily rainfall and air temperature (Hewitson et al., 2004*; Hewitson and Crane, 2006; Lumsden et al., 2009). General circulation models (GCMs) are used for weather forecasting and those predicting climate change are known as global climate models (Hewitson et al., 2004*). GCM simulate the most important features of the climate, namely rainfall and air temperature. Uncertainties are inherent in CGM and predictions of rainfall intensity, frequency and spatial distribution have a lower confidence than for air temperature (Schulze, 2011*). CGMs are commonly downscaled to enable their outputs to be made relevant to regional- or local-scale climate change scenarios (Hewitson et al., 2005*; Hewitson and Crane, 2006). Regional models developed for South Africa demonstrate confidence in pattern changes at a sub-national scale, but lower confidence for the magnitude of change (Hewitson et al., 2005*; Hewitson and Crane, 2006).

Figure 2. South Africa is considered a water scarce country, with the majority of its river systems considered non-perennial. (Credit: 123RF stock photo)

The first WRC project to develop regional climate change projections for South Africa was conducted by Hewitson (1997*). This early model projected reductions of 10-15% in regional summer precipitation extending from the east coast to the central and northern regions of the country, and variable responses for air temperature. Projections were based on only one model and therefore considered to be very preliminary (Hewitson, 1997*). Subsequently, Hewitson (2001*) continued work on global and regional modelling to develop capacity on dynamic modelling for understanding climate change in South Africa, and in 2002, the WRC commissioned a more thorough regional modelling project on climate change and impacts on South African water resources (Schulze, 2005*). Empirical and a regional climate model (RCM) downscaling tools were used to project regional climate change scenarios for South Africa, using regional responses to large-scale circulation change simulated by three GCMs.

Key findings from this study, and supported by subsequent work of Hewitson et al. (2004*) and Hewitson and Crane (2006), included: a wetter escarpment in the east with excessive precipitation over the eastern parts of South Africa during the summertime; a reduction in rainfall over the western region of the country with a shorter winter season in the southwest and a slight increase in intensity of precipitation; and a drying in the far west of South Africa (Schulze, 2005*). Air temperature was projected to increase across the country, with maximum increases in the interior (Hewitson et al., 2005*). More recently, Schulze (2011*) used five IPCC-approved GCMs (Bates et al., 2008) to statistically downscale rainfall projections for 2 600 rainfall stations and 400 temperature stations across South Africa. These climate change models predict that responses will not be uniform within South Africa and climate change is likely to impact most strongly on the western regions, with less of an impact as one moves eastwards. Dallas and Rivers-Moore (2014) summarised the responses of freshwater systems to rainfall and air temperature changes as predicted by the climate change models, with summer and winter rainfall regions given separately where relevant (Table 1). For example, January (summer) maximum temperature is projected to increase by 2–6 °C (Figure 4). Certain areas are likely to become 'winners' in light of certain projected changes, while other areas are likely to become 'losers' as more water-related stresses are experienced. 'Hotspots' of concern are the southwest of the country, the west coast and, to a lesser extent, the extreme north of South Africa (Stuart-Hill et al., 2011*).

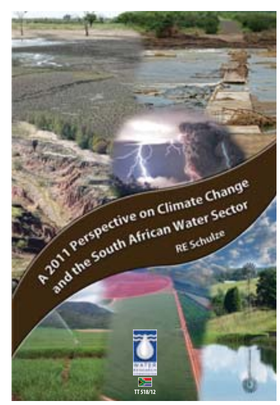


Figure 3. The 2011 study by Schulze used five IPCC-approved GCMs to statistically downscale rainfall projections for 2 600 rainfall stations and 400 temperature stations across South Africa.

Table 1: Responses of rainfall and air temperature for the summer and winter rainfall regions of South Africa as predicted by global climate change models (Hewitson and Crane, 2006; Lumsden et al., 2009; Schulze, 2011*). Published with permission by Dallas and Rivers-Moore (2014).

Predicted change in climatic factors	
Summer rainfall region (central, north, east)	Winter rainfall region (southwest)
Rainfall	
Increase in mean annual precipitation (MAP) of 40 mm to 80 mm per decade in the east, particularly the mountainous areas. Northern and eastern regions likely to become wetter in summer and autumn, especially over regions of steep topography around the escarpment and Drakensberg.	Decrease in MAP of 20 mm to 40 mm per decade. Shorter winter rainfall season, weaker winter pressure gradients, more summer rainfall from January onwards, especially inland and towards the east.
Increase in year-to-year absolute variability of MAP in the east (from 30% up to double).	Decrease in year-to-year absolute variability of annual precipitation.
Wetting trend of varying intensity and distribution, particularly in the east and transitional region. Drying trend in the middle and towards the end of the wet season (i.e. January, April) in northern areas.	Drying trend in the west, mainly in the middle of the rainy season (July) and towards the end of the rainy season (October). Mountainous regions predicted to be relatively stable, while coastal regions likely to become drier.
Greater interannual variability, intensifying in autumn.	Greater interannual variability, more irregular rainfall events.
Increase in intensity of rainfall events.	Increase in the frequency of extreme events, including drought as a result of the predicted poleward retreat of rain-bearing frontal systems.
Air temperature	
Into the IF mean annual temperatures are projected to increase by 1.5–2.5 °C along the coast and by 3.0–3.5 °C in the far interior. Into the MDF mean annual temperatures are projected to increase by 3.0–5.0 °C along the coast and by more than 6.0 °C in the interior. Interannual variability (as standard deviation of annual mean) of temperature is projected to increase by ~10% over much of South Africa, with increases in excess of 30% in the north. Variability in mountainous areas in the south and west is not projected to change (i.e. January, April). July (winter) minimum temperatures are projected to increase by a wider range from <4 °C to >6 °C, but with essentially an increasing south to north gradient from the coast to the interior.	
January (summer) maximum temperature is projected to increase by 2–4 °C.	January (summer) maximum temperature is projected to increase by 4–6 °C.
In KwaZulu-Natal, mean daily air temperature is likely to increase by approximately 2.5 °C.	Increase in days with hot, berg winds during December/January/February.

IF, intermediate future (2046–2065); MDF, more distant future (2081–2100)

Note: model predictions are more in agreement for temperature than for rainfall.

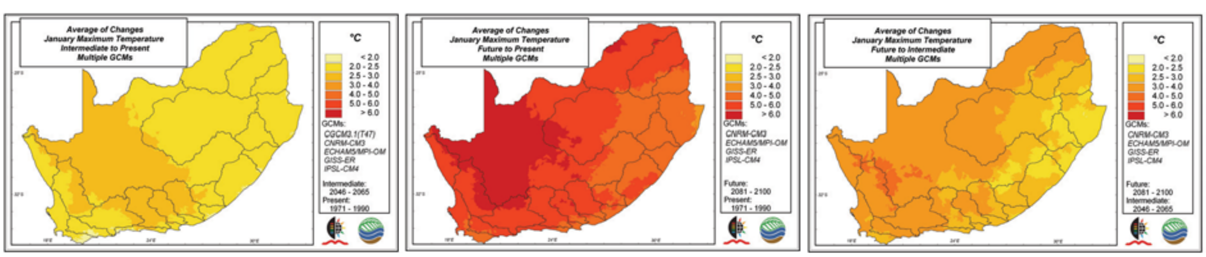


Figure 4: Average of changes (°C), using output from multiple GCMs, of means of daily maximum temperatures for January between the intermediate future and present (left), the more distant future and present (middle) and the more distant and intermediate future climate scenarios (right) From Schulze and Kunz (2011*), page 81.

Impact of climate change of water resources and ecosystems

Climate-change drivers directly affect the quantity of water in aquatic ecosystems by changing runoff patterns (e.g., mean values, flow variability, duration and timing), increasing the frequency and intensity of extreme events (floods and droughts), increasing water temperature and changing groundwater recharge rates (Dallas and Rivers-Moore, 2014). Stressors often act in synergistic ways with effects exacerbated through the interaction of two or more stressors such as the combined effect of reduced runoff and elevated water temperature. Climate change is likely to impact all aquatic ecosystems, including freshwaters (rivers and wetlands), estuaries and groundwater, with pronounced effects on inland freshwater ecosystems through altered precipitation, increased temperatures and more frequent or intense disturbance events (droughts, storms, floods). The impact of climate change on rainfall and catchment runoff is also likely to have a significant impact on estuarine functioning, which is strongly influenced by the magnitude and timing of freshwater runoff reaching them. Climate change affects groundwater levels, recharge rates and groundwater contribution to baseflow, although to date little research has been conducted on the future impact of climate change on groundwater resources in South Africa (Dennis et al., 2013*).

This section focuses on riverine ecosystems, while climate-related studies in other aquatic ecosystems, viz, cross reference wetland chapter, cross reference estuaries chapter and cross reference groundwater chapter, are discussed in the various related chapters. A paper on the ecological consequences of global climate change for freshwater ecosystems in South Africa (Dallas and Rivers-Moore, 2014) – the culmination of a workshop jointly funded by the WRC and World Wildlife Fund in 2009 – provided the basis for this section. The aims of that workshop were: to initiate dialogue between climate-change and freshwater experts; to improve our understanding of the likely consequences of climate change on freshwater ecosystems in South Africa; to document different forecasts that climate change will have on freshwater ecosystems with respect to water resources, the integrity of freshwater ecosystems, social and economy impacts; and to develop a planning framework for investigating possible adaption measures for the impacts of climate change on freshwater ecosystems (Dallas and Rivers-Moore, 2009a).

Freshwater ecosystems are amongst those most vulnerable to climate change (Bates et al., 2008). Observational records and climate projections provide abundant evidence that freshwater resources have the potential to be strongly impacted by climate change, with wide-ranging consequences for human societies and ecosystems (Bates et al., 2008). While historically studies on climate change have focused on terrestrial ecosystems, in the last decade attention has shifted to freshwater ecosystems (Filipe et al., 2013). This shift follows the recognition that freshwater ecosystems are vulnerable to climate change, are highly sensitive to climate change (Durance and Ormerod, 2007; Woodward et al., 2010) and that climate change is expected to worsen freshwater conditions, especially in Mediterranean regions (Filipe et al., 2013). Understanding the consequences of climate change for freshwater ecosystems requires consideration of effects related to water quantity, water quality, physical habitat and biological assemblages.

Impacts of climate change on riverine ecosystems – water quantity

The first major WRC-funded study focusing explicitly on climate change and impacts on South African water resources commenced in 2002 (Schulze, 2005*). Since this study, a substantial body of research has been undertaken in South Africa on the likely consequences of climate change on water resources, in particular rivers (Lumsden et al., 2009; Schulze, 2011*). A quinary catchment is a statistically defined region of uniform topography and relatively homogeneous hydrology falling within a quaternary catchment (Schulze, 2011*). Quinary catchments for South Africa, delineated by Maherry et al. (2013*) provide a valuable spatial unit for many subsequent studies, including the assessment of flow regime types to assist with setting regional water quantity requirements, and in particular, for determining the quantity of water needed in a river or stream (Rivers-Moore et al., 2016). Projected impacts of climate change on hydrological responses have been determined using the Agricultural Catchments Research Unit's (ACRU) process-based, daily time-step agro-hydrological modelling system (Schulze, 2011*). The first versions of ACRU were developed in the 1970s, coincident with the formation of the WRC. Since then, this model has been enhanced and expanded to the point where it is internationally recognised. It was often said tongue-in-cheek that ACRU "grew by degrees", and this is largely due to the funding of students by the WRC over the years.

The projected impacts of climate change on hydrological responses were determined using output from one to five GCMs, empirically downscaled to climate-station level and adjusted to the 5 838 quinary catchments. Predicted hydrological responses include changes in runoff patterns, in the frequency and intensity of extreme events, and in groundwater recharge rates for three 20-year climate time slices: the present (1971–1990), the intermediate future (2046–2065) and the more distant future (2081–2100) (Schulze, 2011*). Runoff is projected to increase over much of South Africa with the exception of the south-western Cape, which will have reduced streamflows especially in wet years, which will be less wet than currently (Schulze, 2011*; Dallas and Rivers-Moore, 2014). The reduction in streamflow would result in a change in perenniality (rivers) or permanence of inundation (wetlands), with perennial rivers becoming non-perennial and permanent wetlands becoming seasonal or temporary. In terms of drought, most parts of South Africa are likely to experience reduced frequency, duration and intensity of droughts, with the exception of the west coast and the north-west, which will experience marked increases in annual droughts (Schulze, 2011*; Dallas and Rivers-Moore, 2014). Floods and stormflow, i.e., the runoff of surface water from rainfall, are predicted to increase across South Africa, particularly in the central west where both magnitude and variability of stormflow will increase (Schulze, 2011*; Dallas and Rivers-Moore, 2014). Projected changes in groundwater recharge rates differ for each time slice and hydrological condition (dry year vs wet year conditions).

Impacts of climate change on riverine ecosystems – water quality

Higher water temperatures, increased precipitation intensity, and longer periods of low flows are projected to exacerbate many forms of water pollution, including thermal pollution, and increased concentrations of salt, sediments, nutrients, dissolved organic carbon, pathogens and pesticides (Bates et al., 2008). Climate-change drivers (rainfall and air temperature) primarily affect the quality of water in freshwater ecosystems by changing water temperature. Changes in water temperature may affect the solubility of oxygen and other gases, for example, decreasing the concentration of dissolved oxygen; altering the concentrations of inorganic nitrogen, phosphorus and un-ionised ammonia; modifying microbial activity; and changing chemical reaction rates and toxicity of chemicals such as atrazine, cadmium, cyanide, fluoride, lead, phenol, selenium, xylene, and zinc (Dallas and Day, 2004*; Dallas, 2008; Dallas and Rivers-Moore, 2019b*, 2021). Turbidity, nutrients, suspended sediments, metals, pesticides, and pathogens may also increase in response to more intense rainfall events, while in semi-arid and arid areas, salinity may increase as a result of increased evaporation from shallow ground and surface water (Dallas and Rivers-Moore, 2019b*, 2021). The quality of water in many South African rivers and wetlands is already widely compromised, and climatic drivers therefore act as additional stresses on these ecosystems (Dallas and Rivers-Moore, 2014). The effects of water quality variables on aquatic ecosystems have been widely documented (Dallas and Day, 2004*), with specific studies focusing on particular variables, including water temperature (Dallas, 2008).

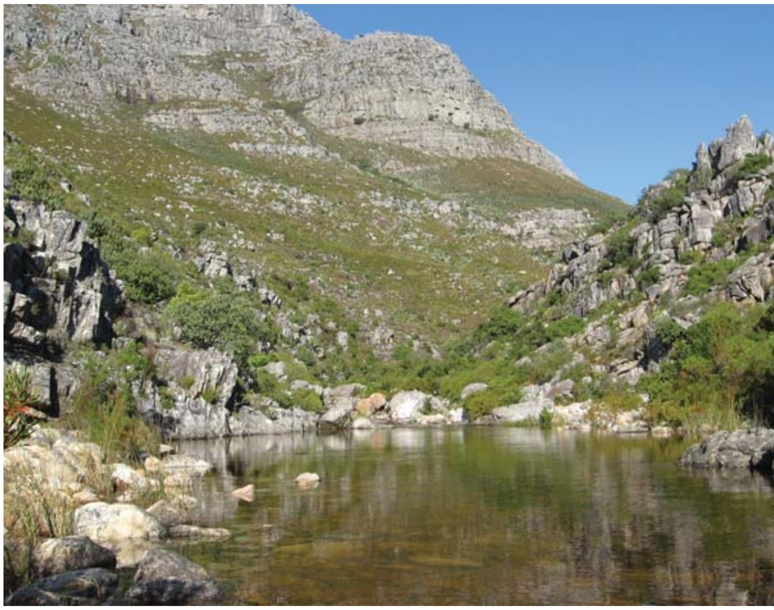


Figure 5. Wit River in the Western Cape . Environmental water temperature guidelines have been developed for South Africa's perennial rivers. (Credit: Helen Dallas/Water Wheel archives)

Early water temperature data relied on minimum/maximum thermometers that were usually checked on a monthly basis. These data were collected since it was recognised that fish community assemblages in the Sabie River were fundamentally structured around temperature preferences (Weeks et al., 1996*). With the advent of relatively cheap yet reliable electronic temperature logging devices, recording continuous temperature data became increasingly viable from the early 2000s. Locally, the WRC funded the development of miniaturised water temperature loggers (Harding and Jarvis, 2007*; 2010*), which since being patented in 2013, provide a potentially low-cost, local solution to water temperature monitoring in South Africa. Several WRC studies have focused on water temperature in rivers (Rivers-Moore et al., 2004*; 2008*; Dallas, 2009*; Dallas and Rivers-Moore, 2012a*; Dallas et al., 2015*; Dallas and Rivers-Moore 2019a*,b*) (Table 2), with the first water temperature loggers installed in 2001 on the Sabie River under the umbrella of the WRC-funded Kruger National Parks Rivers Research Programme (Rivers-Moore et al., 2004*).

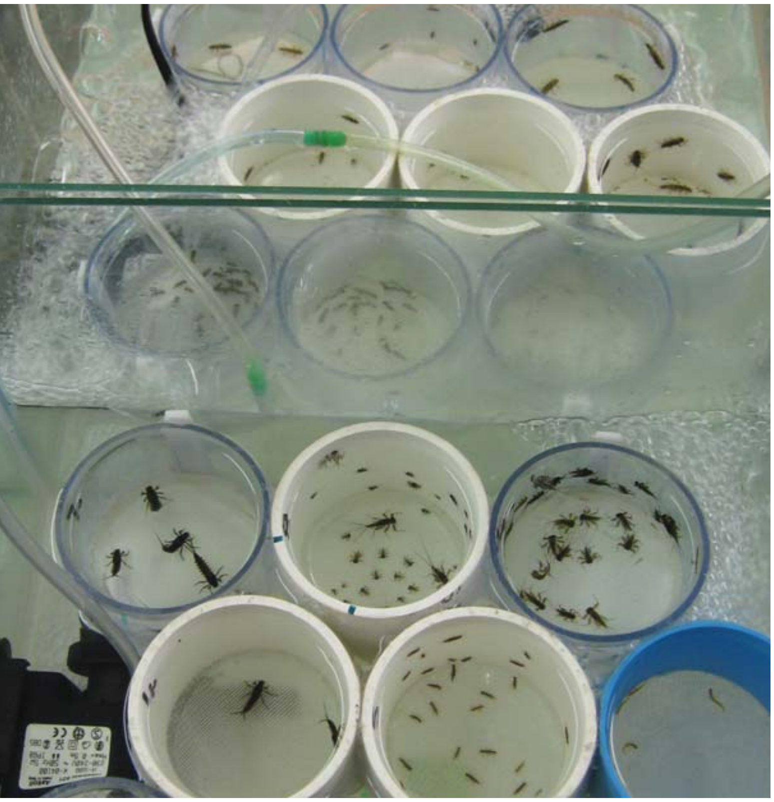


Figure 6. Thermal experiments to determine upper temperature limits undertaken to assess the impact of climate change on river systems. (Credit: Helen Dallas/Water Wheel archives)

That study provided some of the first longer-time continuous hourly measurements of water temperature over a two-year period. Since then, sub-daily (mostly hourly) water temperature has been logged approximately 200 sites around South Africa (Table 2). In addition, associated projects such as the Table Mountain Group Aquifer project (FCG, 2014a, b, c, d) and others have collected sub-daily water temperature data, together with flow data. The data generated from these studies provide an immeasurably valuable resource for examining thermal signatures of river systems around the country, and, in the absence of an official water temperature monitoring programme, present the only water temperature data available on South African rivers. For some studies, two-hourly air temperature data was also recorded to facilitate the development of air-water temperature models (Dallas and Rivers-Moore, 2012a*).

Figure 7. The 2012 study by Dallas and Rivers-Moore made use of water temperature loggers housed in a protective metal casing. (Credit: Helen Dallas/Water Wheel archives)

Table 2: WRC funded studies, and in some cases associated theses, that collected water temperature using water temperature loggers.

Report	River(s)	Time period
RIVERS-MOORE NA, JEWITT GPW, WEEKS DC and O'KEEFFE JH (2004) Water temperature and fish distribution in the Sabie River system: Towards the development of an adaptive management tool. Water Research Commission Report No. 1065/1/04. Water Research Commission, Pretoria, South Africa.	Nine sites on the Sabie River, Mpumalanga.	2000-2002
PAXTON BR and KING JM (2009) The influence of hydraulics, hydrology and temperature on the distribution, habitat use and recruitment of threatened cyprinids in a Western Cape river, South Africa. Water Research Commission Report No. 1483/1/09. Water Research Commission Pretoria, South Africa.	One site on the Driehoeks River, Western Cape.	2004-2006
EWART-SMITH JL and KING JM (2012) The relationship between periphyton, flow and nutrient status in south-western Cape foothill rivers and the implications for management. Water Research Commission Report No 1676/1/12. Water Research Commission, Pretoria, South Africa.	Two sites on the Berg River and one on the Molenaars River, Western Cape.	2007-2009
KETLEY Z (2009) Stream invertebrates and water temperature: Evaluating thermal tolerances in the Cape Floristic Region (South Africa) - implications of climate change. PhD thesis, University of Cape Town.	Six sites on Window Gorge stream, Kirstenbosch, Western Cape.	2008-2009
DALLAS HF and RIVERS-MOORE NA (2012a) Water temperatures and the Reserve. Water Research Commission Report No. 1799/1/12. Water Research Commission, Pretoria, South Africa.	88 sites on 56 rivers in the Western, Southern and Eastern Cape. Air temperature at 46 sites on 42 rivers.	2009-2010
FRESHWATER CONSULTING GROUP (FCG) (2014) Table Mountain Group Aquifer (TMGA) Ecological and Hydrogeological Monitoring project. Resource & Infrastructure Planning (Bulk Water), City of Cape Town.	Nine sites on seven rivers, Western Cape. Air temperature also recorded.	2011-present
DALLAS HF, RIVERS-MOORE NA, ROSS-GILLESPIE V, RAMULIFHO P and REIZENBERG J (2015) Adaptability and vulnerability of Riverine Biota to Climate Change – Developing Tools for Assessing Biological Effects. Water Research Commission Report No. 2182/1/15. Water Research Commission, Pretoria, South Africa.	18 sites on rivers in the Western Cape, Southern Cape, Eastern Cape, Mpumalanga and KwaZulu-Natal.	2013-2014
PAXTON BR, DOBINSON L, KLEYNHANS M and HOWARD G (2016) Developing an elementary tool for Ecological Reserve monitoring in South Africa's Freshwater Ecosystem Priority Areas (FEPAs): a pilot study in the Kouebokkeveld. Water Research Commission Report No. WRC Report No. 2340/1/16. Water Research Commission Pretoria, South Africa.	Two sites (Twee and Riet Rivers) in the Kouebokkeveld, Western Cape.	2013-2019
PAXTON BR (2021) Unpublished data. FRC Cape Critical Rivers Project: Saving Barrydale redfin.	Two sites on the Huis River, Barrydale, Western Cape.	2013-2015
PAXTON BR (2021) Unpublished data. FRC Cape Critical Rivers Project: Saving Sandfish.	Two sites on the Oorlogskloof River, Northern Cape.	2015-2017
EWART-SMITH JL, ROSS-GILLESPIE V and GRAINGER C (2017) The development and application of periphyton as indicators of flow and nutrient alterations for the management of water resources in South Africa. Water Research Commission Report No. TT 784/18. Water Research Commission, Pretoria, South Africa.	Two sites on the Mzunduzi River, two on the uMngeni River and one on the Hklatikhulu River, KwaZulu-Natal.	2014-2015
DALLAS HF, SHELTON S, PAXTON BR, WEYL O, REIZENBERG R, BLOY L and RIVERS-MOORE NA (2019) Assessing the effect of climate change on native and non-native freshwater fishes in the Cape Floristic Region, South Africa. Water Research Commission Report No. TT 801/19. Water Research Commission, Pretoria, South Africa.	Multiple sites (> 50) on the Amandel and Berg Rivers in the Western Cape.	2015-2016
REIZENBERG J, BLOY I, WEYL O, SHELTON J and DALLAS HF (2019) Variation in thermal tolerances of native freshwater fishes in South Africa's Cape Fold ecoregion: examining the east–west gradient in species' sensitivity to climate warming. J. Fish. Biol. 94 (10) 103-112.	Driehoeks, Rondegat, Amandel, Berg Rivers in the Western Cape and the Fernkloof River in the Eastern Cape.	2015-2017
RIVERS-MOORE NA and PALMER R (2017) Development of a predictive management tool for Orange River blackfly outbreaks. WRC Project No. K5/2459, Water Research Commission, Pretoria.	Nine sites along the middle and lower Orange River, Northern Cape.	2015-2016
OLSEN T, SHELTON SM and DALLAS HF (2021) Does thermal history influence thermal tolerance of the freshwater fish Galaxias zebratus in a global biodiversity hotspot? J. Therm. Biol. 97: 102890. doi.org/10.1016/j.jtherbio.2021.102890.	Eleven sites on six rivers (Liesbeek, Diep, Schusters, Silvermine, Admirals Kloof and Disa Rivers) on the Cape Peninsula, Western Cape.	October 2017 to April 2018
RAMULIFHO PA, FOORD S, and RIVERS-MOORE N (2019) Modelling flow and water temperature in the Luvuvhu catchment and their impact on macroinvertebrate assemblages. PhD Thesis, University of Venda, Thohoyandou, South Africa.	Ten sites on six rivers (Dzindi, Lutanandwa, Luvuvhu, Mutale, Mutshundudi, Tshirovha Rivers) in the Luvuvhu Catchment, Limpopo Province.	2016 to 2018

Report	River(s)	Time period
REIZENBERG J (2021) The Giant Redfin (Pseudobarbus skeltoni) and Climate Change: Assessing the effect of key physico-chemical parameters and biological traits on the distribution of an endangered native freshwater fish species in the Cape Fold Ecoregion. PhD thesis, University of Cape Town.	Multiple sites with 6 months data (> 50) and eight sites with one year data on Tierkloof River, and two sites on the Riviersonderend River, Western Cape.	2019-2020
Freshwater Research Centre (2021) Unpublished data. The Nature Conservancy Monitoring & Evaluation project.	Two sites (Du Toits and Riviersonderend Rivers), Western Cape	2019-2021
DALLAS H (2021) Unpublished data	Several rivers in the vicinity of Cape Town, including the Berg, Diep, Eerste, Elandspad, Molenaars, Rooielskloof, Silvermine, Skeleton Gorge, Window Gorge, Witte Rivers.	Variable periods within the years 2009-2020

Over the last two decades, using these thermal time series as primary data, ecological research has been undertaken in numerous river systems across South Africa (Rivers-Moore and Jewitt, 2004; Rivers-Moore et al., 2004*; 2005a; 2008*; Dallas, 2008; Dallas and Rivers-Moore, 2012a*; Dallas et al., 2015; Dallas and Rivers-Moore, 2019a*,b*, 2021; Dallas et al., 2019*), including thermal variability (Dallas and Rivers-Moore, 2011), development of air-water temperature models (Rivers-Moore and Lorentz, 2004; Rivers-Moore et al., 2005b; Dallas and Rivers-Moore, 2012a*; Rivers-Moore et al., 2012), generation of indicators of thermal alteration (ITA) and thermographs (Rivers-Moore et al., 2012; 2013a), creation of national maps and databases of thermal resilience and air-water model accuracy (Dallas and Rivers-Moore, 2019a*, b*), and indices for managing water temperature (Rivers-Moore et al., 2005a; 2016). Protocols and tools have been developed for establishing environmental water temperature guidelines and setting thermal targets (Rivers-Moore et al., 2013a; 2015; Dallas et al., 2015*; 2019*; Dallas and Rivers-Moore 2019a*, b*, 2021). These are discussed further in the section 'Managing water temperatures in South African rivers'.

Impacts of climate change on riverine ecosystems – physical habitat

Changes in the amount, intensity and seasonal distribution of rainfall affect channel geomorphology; lateral, longitudinal, and temporal connectivity; and aquatic habitat, through changes in runoff (Dallas and Rivers-Moore, 2014). While geomorphological studies in South Africa have not focused specifically on climate change (see chapter on rivers), observations elsewhere are likely to be applicable, with many effects similar to those already observed following the construction of impoundments and abstraction of water. Geomorphological changes from increased discharge may include, greater channel instability and sinuosity, and increased bank erosion, while decreased discharge may result in channel shrinkage, greater channel stability, vegetation encroachment, and sedimentation in side-channels (Dallas and Rivers-Moore, 2014). Loss of lateral, longitudinal and temporal connectivity can lead to isolation of populations, failed recruitment and local extinction; the maintenance of natural connectivity patterns is thus essential to the viability of populations of many riverine species and for maintaining instream integrity (Bunn and Arthington, 2002). Connectivity is typically reduced through flow regulation by dams and is often compounded by other structural modifications such as channelization. Ecological processes in rivers are disrupted when upstream-downstream connectivity is broken (Rivers-Moore et al., 2016; Ramulifho et al., 2018). The development of a multi-metric connectivity index facilitates the quantification of river connectivity holistically (lateral, longitudinal and temporal components), providing a basis for identifying areas of vulnerability of aquatic biota to disturbances such as the effects of climate change using suitable scenario models (Dallas et al., 2015*; Rivers-Moore et al., 2016). In streams, flow is a major determinant of physical habitat, which in turn is a major determinant of biotic composition. Studies examining changes in physical habitat and biota, in particular changes in flow, include a study on fish (Paxton and King, 2009*) and aquatic invertebrates (Tharme, 2010), the latter where manipulated low flows resulted in consistent, marked declines in physical habitat availability for aquatic invertebrates. Regions predicted to have decreased flow are therefore likely to exhibit increased fragmentation of existing instream and riparian habitats, with resultant loss of habitat and connectivity.

Impacts of climate change on riverine ecosystems – biological assemblages

Research on understanding the physical nature of water temperature in river ecosystems, in particular ITAs and thermographs, has provided a landscape-scale framework for subsequent climate-related research focusing on biological responses of aquatic organisms, both at the individual and community level. Effects of changes in water temperature on river organisms may include individual- and population-level modifications such as alteration of individual life history patterns, increases in the number and spread of invasive and pest species (for example, blackfly species such as ***Simulium chutteri***), increase in waterborne and vector-borne diseases (cholera, malaria, etc.), extinction of vulnerable species, shifts in species distribution and range, and changes in communities and aquatic biodiversity (Rivers-Moore et al., 2004*; 2013b; 2014; Dallas and Rivers-Moore, 2014; Rivers-Moore and Palmer, 2017*). Biotic responses to climate change, and in particular water temperature, have been investigated experimentally for aquatic insects (Dallas and Ketley, 2011; Dallas and Ross-Gillespie, 2015; Dallas et al., 2015*; Dallas, 2016; Dallas and Rivers-Moore, 2018; Ross-Gillespie et al., 2018; Dallas et al., 2019*) and fish (Reizenberg et al., 2019; Olsen et al., 2021).

Figure 8. Blackfly larvae on the banks of the Orange River. (Credit: Nick Rivers-Moore/Water Wheel archives)

Achievements include the development and utilisation of laboratory methods for measuring thermal tolerance of aquatic insects (Dallas et al., 2015; Dallas, 2016; Dallas and Rivers-Moore, 2018) and fish (Reizenberg et al., 2019; Olsen et al., 2021), development of methods to measure sub-lethal thermal effects such as egg development (Dallas and Ross-Gillespie 2015; Ross-Gillespie et al., 2018) and thermal preference (Dallas et al., 2019*). Field surveys have been undertaken to examine individual species (Dallas and Rivers-Moore, 2012b; Ross-Gillespie, 2014) and community responses to changes in water temperature and flow (Eady et al., 2013; Dallas et al., 2015*; Shelton et al., 2018a, b). Species distribution and logistic regression models have been used to predict the impact of climate warming on native, non-native and pest species (Rivers-Moore et al., 2013b; Rivers-Moore et al., 2014; Dallas et al., 2019*).

Through this research it has become clear that there are distinct 'winners' and 'losers' in terms of biological responses to climate change and, in particular, climate warming. Upper thermal tolerance limits varied spatially and temporally, and thermal limits are strongly influenced by thermal history, i.e., ambient water temperature of the stream or river where the organism is living (Dallas et al., 2015*; Olsen et al., 2021), confirming that thermal guidelines need to be developed for both regional and local scales. For aquatic insects, life-history responses appear to be finely attuned to thermal regimes, while the hydrological regime was noted as a driver determining population size and mortality (Ross-Gillespie, 2014; Dallas et al., 2015*). Field studies of climate change often adopt the approach of examining relationships between species and temperature, or flow, and then scaling up those relationships to estimate changes in species distributions under different climate change scenarios, or modelling probabilities of occurrence or chronic thermal stress using, for example, logistic regression models. Species distribution models (SDMs) developed for native and non-native fish species in the Cape Fold Ecoregion (Dallas et al., 2019*; Shelton et al., In prep.) showed that the geographic ranges of native fish species are likely to become restricted to differing degrees. The SDMs provide a potentially valuable tool for achieving conservation objectives – particularly for identifying climate change refugia for species at risk – and can inform water resource management and river rehabilitation priorities, as well as long-term conservation planning (Dallas et al., 2017; 2019*).

For aquatic insects, probabilities of hatching and breeding success, plus population sizes and generation numbers per month, under current and projected 2°C warmer water temperature scenarios, were modelled using spreadsheet and logistic regression probability models. The results suggest that cold-adapted Gondwanaland relict species are likely to become increasingly vulnerable and range limited, whereas multivoltine pest species are likely to become more abundant under scenarios of increased water temperatures (Rivers-Moore et al., 2013b). The latter may have substantial economic fallout, as demonstrated by the projected economic losses resulting from the synergistic impacts of flow regulation and warmer water temperatures on pest blackfly outbreaks along the middle and lower Orange Rivers (Rivers-Moore and de Moor, 2020). It is important to reiterate that climate change is often an added stress to already over-allocated and stressed ecosystems, with over-abstraction, in particular, likely to interact with other climate change impacts to reduce flow and dissolved oxygen levels and raise water temperatures beyond a species' environmental tolerance limits (Dallas et al., 2019*).

Adapting to climate change

National responses to climate change should include adaptation, mitigation, technological development and research (Green, 2008*), and proactive strategies are needed at local and national level to deal with the impacts of climate change and drought on water resources (Mukheibir and Sparks, 2006*). Schulze (2011*) provided a comprehensive discussion on climate-proofing the South African water sector, with practical suggestions for adaptation to climate change. Since then, the WRC has funded various projects to investigate the adaptive capacity of small towns and communities in the Northern Cape province to climate variability, specifically drought (Mukheibir and Sparks, 2006*), to develop a water sector guide of the most relevant adaptation technologies and approaches to climate change over the short, medium and long term for local government institutions, especially municipalities in South Africa (Dube et al., 2016*); to engage with rural communities in planning for climate change adaptation at a local level (Hay and Hay, 2014*), and to develop a decision-support framework for an adaptive management strategy to assess and modify water services delivery and development plans of Water Boards (Hughes et al., 2014*). Each of these studies speaks to water resources in South Africa at multiple levels but since the focus of this chapter is on riverine ecosystems, we discuss these in more detail below.

Nature has a strong role to play in climate change adaptation, especially water storage and flood control, and promotion of nature-based solutions (NBSs) will ultimately help to reduce costs and increase cost-effectiveness of engineered infrastructure and increase the co-benefits, including biodiversity conservation. NBSs use or mimic natural processes to increase water availability (e.g. soil moisture retention and groundwater recharge), improve water quality (e.g. natural and constructed wetlands and riparian buffer strips), and reduce water-related risks by restoring flood plains and constructing decentralised water retention systems, such as green roofs (United Nations, 2018). From a climate change perspective, climate resilience can be strengthened through services provided by healthy ecosystems that rely on well-functioning river catchments.

Figure 9. Climate resilience can be strengthened through services provided by healthy ecosystems. (Credit: 123RF/ Stock photo)

Managing and mitigating the impacts of climate change on water resources

There is consensus that, other than mitigating greenhouse gas emissions, the most effective way to address the effects of climate change on ecological systems is to focus on building ecological resilience through promoting adaptation of species and ecosystems to climate change impacts (Wise et al., 2014). Resilience in an ecological context reflects the capacity of natural systems to withstand and recover from environmental change and thus persist into the future. Systems that are more resilient are better able to adapt to changes in climate and ecosystem resilience is key to reducing the consequences of global climate change on aquatic ecosystems (Dallas and Rivers-Moore, 2014). Recently, Rivers-Moore and Dallas (In prep.) developed a database of variables likely to indicate riverscape resilience to thermal stress. Resilience of a river is likely to be affected by variables such as stream order, groundwater depth, flow predictability, water yield (i.e., precipitation minus evaporation) and catchment transformation. The resilience ratings for each variable are summed to generate a Total Resilience Score for each sub-catchment and used to generate a map of system resilience to thermal stress for South Africa. Identifying resilience hotspots in rivers enables targeted conservation action when funding is limited and defining relative ecosystem resilience is important for evaluating the potential consequences of climate change on aquatic ecosystems.

Realistically, very little can be done directly to mitigate impacts on water temperature, and the most practical approach is to mitigate insulators, which influence the rate of heat exchange with the atmosphere, and buffers, which store heat already in the system and integrate the variation in flow and temperature over time. To enhance the resilience of freshwater ecosystems, specific, proactive restoration, rehabilitation, and management actions are advocated (Dallas and Rivers-Moore, 2014). Ways to promote ecosystem resilience include, for example, maintaining environmental flows, restoring instream, riparian and wetland habitat, restoring and maintaining connectivity within river networks, and recognising the link between catchment condition and freshwater ecosystem health (Dallas and Rivers-Moore, 2014).

Managing water temperatures in South African rivers

Effective management of water temperature requires an understanding of the thermal dynamics and biotic responses to changes in water temperature. The establishment of thermal guidelines that adequately protect aquatic ecosystems and their biota is dependent on an understanding of a river's thermal signature and the vulnerability of its biota to changes in water temperature (Dallas et al., 2015*). Over the last decade and a half, research on water temperature, including the biotic responses of aquatic organisms to climate warming in particular, have substantially increased our understanding of thermal signatures of rivers, and the sensitivity and vulnerability of the biota living in these rivers. Most recently, Dallas and Rivers-Moore (2019*, b*, 2021) translated this thermal research on South African rivers into a protocol for practitioners and decision-makers responsible for managing water temperature and protecting our river ecosystems. Resources include tabulated reviews of key thermal impacts and their prevalence in South African rivers, and of the biological effects of changes in water temperature on river organisms.

National-scale tools include a spatial framework within which air-water temperature models are applied in relation to national maps of air temperature-water temperature model accuracy and choice of upland versus lowland models, and a national map of system resilience. Both the system resilience and air temperature-water temperature model accuracy maps include an underlying database of variables likely to indicate system resilience and model accuracy. These data form the basis for developing reference thermographs (Figure 10) which reflect one or more thermally homogenous sites using hourly water temperature data and provide a natural range of variability using a thermal confidence envelope. Other innovative tools have been developed for generating thermal metrics and thermographs, and for generating a Thermal Sensitivity Index and identifying thermally sensitive taxa. A protocol for collecting water temperature data, including recommendations on selecting appropriate water temperature loggers, building logger housings and on-site installation methods, has been developed. The protocol developed for establishing environmental water temperature guidelines and setting water temperature targets for perennial rivers in South Africa includes a screening process to assess thermal risk; and an evaluation process to assess thermal change based on deviation from reference or expected thermal conditions (Dallas and Rivers-Moore, 2019a*, b*, 2021).

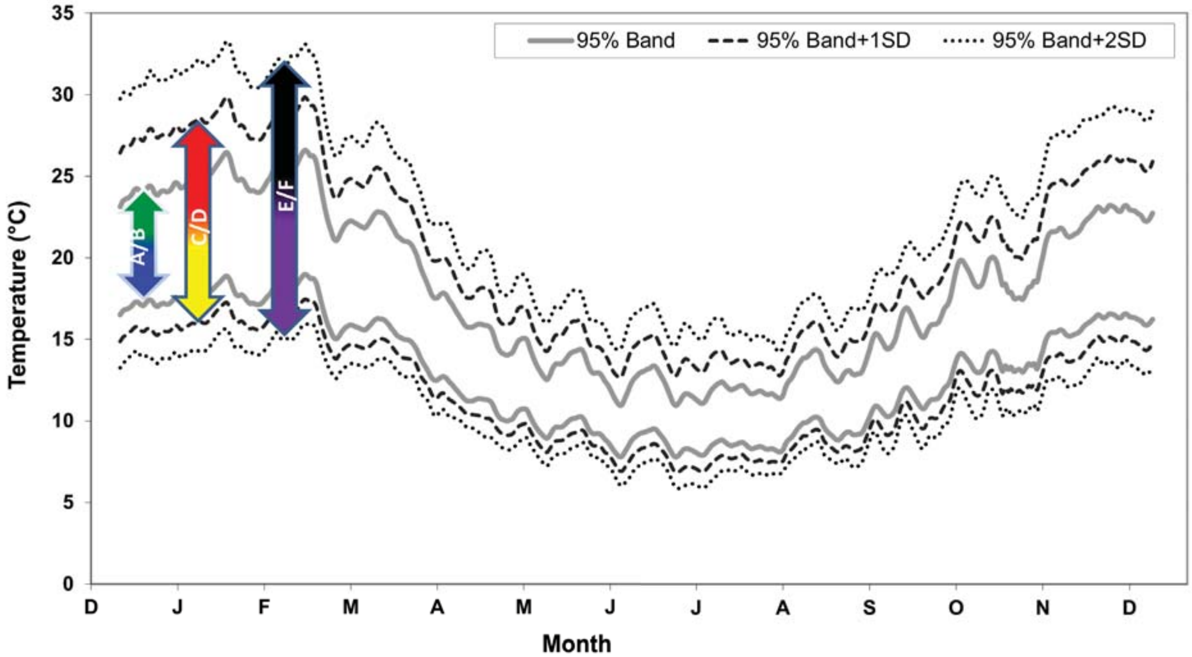


Figure 10. Reference thermograph indicating a reference condition thermal envelope plus one and two standard deviations (Dallas and Rivers-Moore, 2019b*, 2021). The associated Ecological Category (Kleynhans and Louw, 2007*) for each is indicated.

Conclusions and the way forward

Substantial advances have been made in climate-related research in South Africa over the last 20 years, with much of it funded by the WRC. Our understanding of the abiotic drivers of climate change and the projected responses of these key variables to climate change have grown exponentially over the last two decades. This understanding is critical, as the timing is commensurate with the growing climate-change-induced crisis particularly affecting freshwater ecosystems.

While uncertainties will always remain when it comes to models and modelling, the capacity and knowledge of the individuals and research groups involved in climate change modelling in South Africa has advanced considerably since 1990. Similarly, the knowledge of researchers focusing on water temperature in riverine ecosystems has grown enormously and has been expanded to numerous students through the life of the WRC-funded thermal and climate-change projects. Early WRC-funded work such as the Kruger National Park Rivers Research Programme initiated in 1988 (Breen et al., 2000*), identified water temperature as a key driver in ecosystems, which led to the initial study of biotic responses to water temperature and flow undertaken on the Sabie River in the early 2000s (Rivers-Moore et al., 2004*). The foresight of former WRC research manager, Dr Steve Mitchell, in 2005 resulted in the funding of three thermal consultancies (Harding and Jarvis, 2007*; Rivers-Moore et al., 2008*; Dallas, 2009*) with each researcher focusing on different aspects of water- temperature-related research. This culminated in the writing of the Terms of Reference for a long-term temperature programme that incorporated three broad themes: monitoring and modelling, biological responses, and management. The subsequent collaborative research project (2008-2011, Dallas and Rivers Moore, 2012a*) launched the comprehensive programme on water temperature in river ecosystems. Follow-on projects (Dallas et al., 2015*; 2019*; Dallas and Rivers Moore, 2019a*, b*, 2021) built on this foundational research such that laboratory, field and modelling studies greatly increased our understanding of water temperature and the ecological consequences of climate change on aquatic organisms and ecosystems. Translation of this research into innovative protocols and tools for managing water temperature in riverine ecosystems, and in particular for setting environmental water temperatures and thermal targets, has always been a priority for the researchers. The knowledge generated supports the uptake of research into water resource protection, conserving planning (Ramulifho et al., 2018) and policy (Bragg et al., 2017). Bridging the gap between scientific research and resource management, although challenging, is crucial. Further action is recommended to encourage use of the protocols and tools across the various water resource, biodiversity and conservation sectors.

Several gaps or needs have been identified during the development of this chapter. Firstly, long-term data are inherently valuable for evaluating the effects of climate change on aquatic ecosystems. What criteria should be used for strategically selecting sites to serve as sentinel sites for evaluating the potential impacts of climate change? How can monitoring of these sites be integrated into existing institutional business plans in the future and what alternative monitoring actions can be incorporated? The rollout of a national water temperature monitoring programme was identified as a need strongly endorsed by all end-users and stakeholders involved in the participation process of Dallas and Rivers-Moore (2019a*, b*, 2021). This programme will need to be driven by government but will require co-ordination and support of multiple organisations that have a vested interest in tracking long-term change in water temperature.

Secondly, the automation of the processes developed in Dallas and Rivers-Moore (2019a*, b*) into a relevant information system that streamlines the input and output of data required for managing water temperature and setting thermal targets, was recognised as an important requirement to end-users. This includes the automation of the analysis of water temperature time series data into thermal metrics and thermographs to provide thermal signatures for a river. Automation of these processes will encourage the collection of water temperature data across a large segment of water resource practitioners and allow for the mobilisation of existing water temperature data collected by WRC project team members and other researchers in South Africa. While aspects of this are currently being incorporated in the Freshwater Biodiversity Information System (FBIS) (Dallas et al., 2021) further funding is required to mobilise thermal and associated biodiversity data in South Africa.

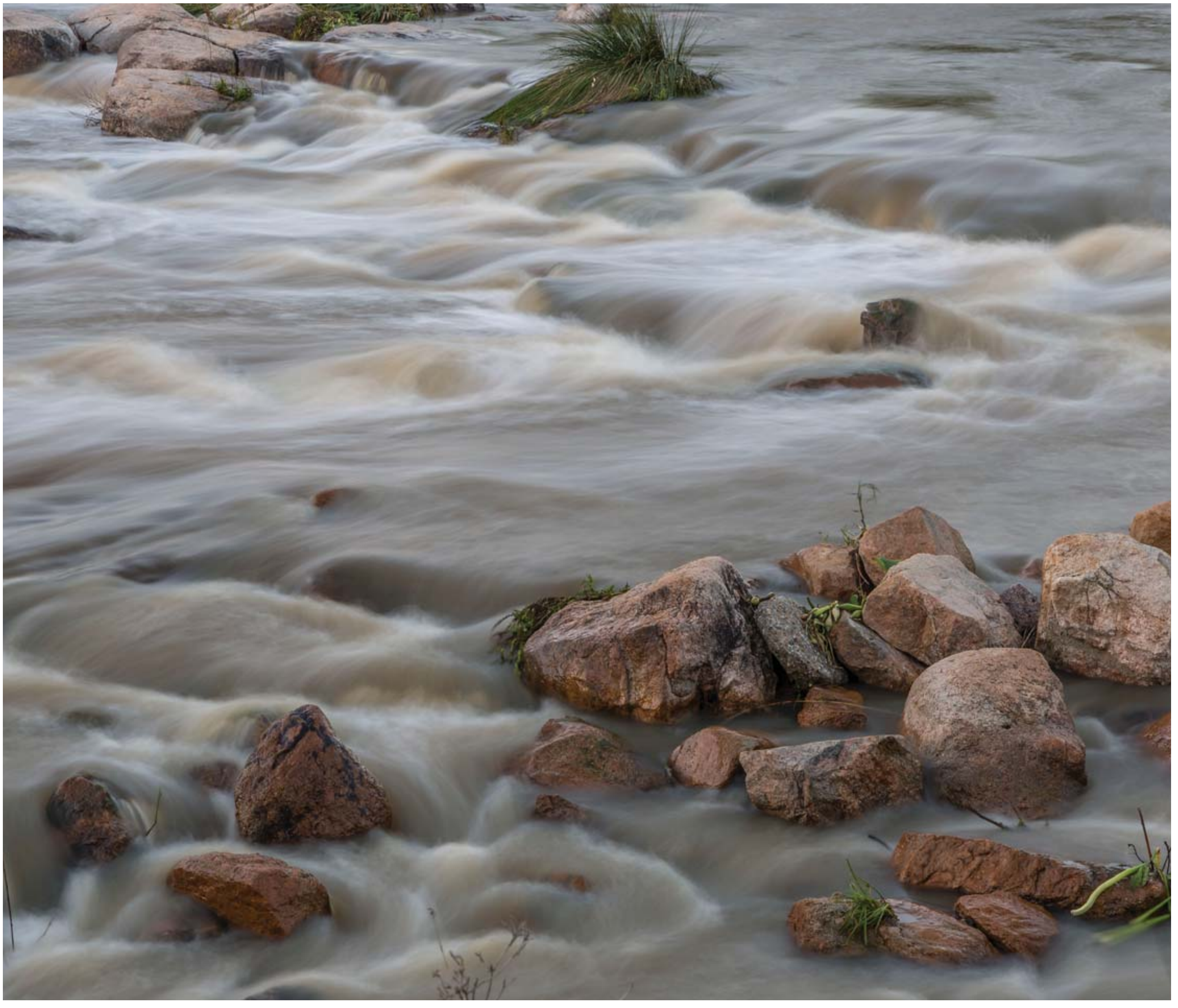
Thirdly, research on potential range shifts of aquatic biota, and how these can be met in relation to river connectivity, needs to be extended. Such information should, in turn inform freshwater conservation planning initiatives (such as the WRC-funded National Freshwater Ecosystem Protected Areas) to understand how effective current reserve networks will be in conserving species in the future.

Lastly, whilst the importance of groundwater in rivers and thermal buffering properties of groundwater is well recognised, the potential consequences of groundwater abstraction on water temperatures in rivers that are largely groundwater dependent is not yet fully understood. A study focusing on this aspect would be beneficial and improve our understanding of the links between surface water, groundwater, water temperature and biological consequences. In particular, managing groundwater protection and utilisation, groundwater recharge dynamics under climate change, and artificial recharge of aquifers as an adaptation measure, should be investigated.

Water and freshwater ecosystems are an integral component of three Sustainable Development Goals, including SDG 6 (Ensure availability and sustainable management of water and sanitation for all), SDG 13 (Take urgent action to combat climate change and its impacts) and SDG 15 (Protect, restore and promote sustainable use of terrestrial ecosystems, sustainably manage forests, combat desertification and halt and reverse land degradation, and halt biodiversity loss). A common thread throughout the SDG dialogue is that effective water resource management needs more and better data since data underpin good water governance. The Water Research Commission has been instrumental in developing institutional and individual capacity and generating knowledge on climate change and freshwater ecosystems in South Africa.

Acknowledgments

The authors are enormously grateful to the many students and research collaborators with whom they have worked over the last two decades of climate change and thermal research. The support of the Water Research Commission has been instrumental in growing our understanding of climate change, especially from the Water Resources and Ecosystems perspective and we gratefully acknowledge the research managers who have supported our projects (Dr Steve Mitchell; Mr Bonani Madikizela; Dr Brilliant Petja). In addition, a whole cohort of researchers have developed capacity and experience through the support of the Water Research Commission.



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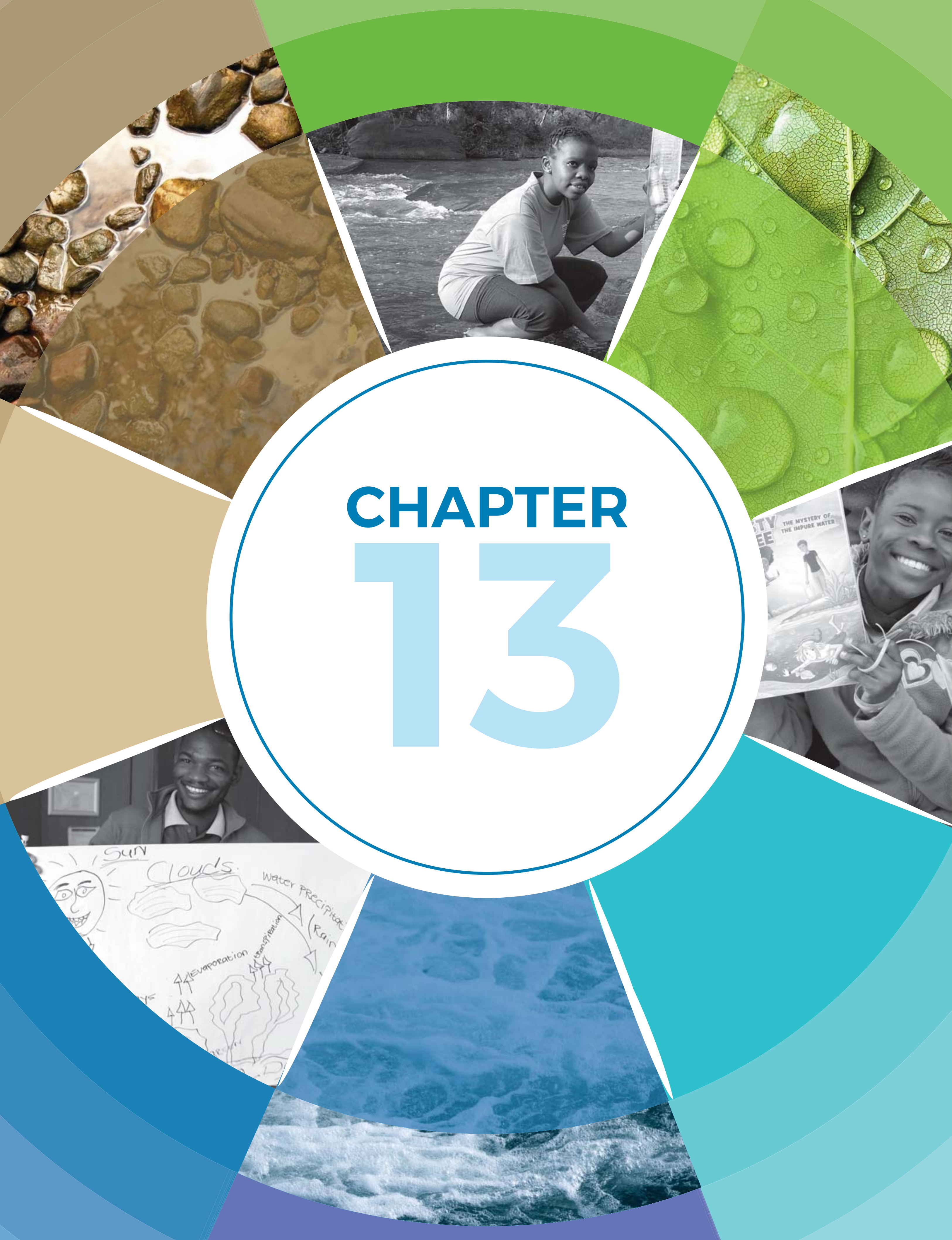


CONCLUDING PERSPECTIVES

Tally Palmer and Jody Reizenberg

The Water Research Commission: a key South African asset

The work reported in this volume shows a depth, breadth and continuity of water-related knowledge-building in South Africa during the last half-century, always remembering the ideals expressed in the original WRC mandate (***see Introduction***). During this period, South Africa has undergone social, technical, economic, environmental and political transformations, which we view here through the lens of water.

In South Africa today, domestic water is more fairly distributed to more people than in the past, but not fairly or reliably enough. Waterborne sanitation and sewage treatment are more extensive but are unsustainable in terms of volumes of water required, while the country faces failing infrastructure, causing disease, hardship and environmental damage. Water drives economic activity in agriculture, industry and mining, but demand exceeds supply. The effects of industrial waste on water quality are severe. Innovation is driving technical solutions – but not everything has a technical solution. The ecological infrastructure is buckling.

Pollution is rife, environmental flow allocations are inadequately implemented, there is structural damage to rivers, wetlands and aquifers – and immediate development trumps the long-term view of sustainability, in terms of the economy as well as ecosystems. In these ways our South African water story matches that of a planet faced with increasing social inequity and environmental failure. Governments worldwide are finding it increasingly hard to plan for human well-being, equitably and with future security. Greed drives consumptive societies, fearful of sharing resources, and spreaders of misinformation. Scientific research is an invaluable push-back against ignorance: Research nurtures imagination, perseverance and adaptation. South African water research has consistently positioned the nation well, to take leading steps in facing water-related challenges.

The Water Research Commission: positioning South Africa as a global leader in water

The Water Research Commission has undergone radical transformation over the past 50 years. The first annual report of the WRC listed the emergent water issues of the time: uncertainty in rainfall patterns and the distribution of water, wasteful irrigation practices, inadequate catchment management, inefficient water-use, pollution, and the condition of underground water all featured among the 'hard' concerns of the WRC. Inadequate training, unsatisfactory coordination and publication of water research and development were also mentioned as areas that required attention.

Today, a half-century after the inaugural meeting of the WRC in September 1971, the WRC boasts a research support structure organised into three core lineages: Water Resources and Ecosystems, Water Use and Wastewater, and Water Utilisation in Agriculture, which were previously organised as key strategic areas of research. They comprise focused thrusts and themes that reach deeply into and across the water value chain. Linkages between these strands are encouraged through seven 'lighthouses' of inter-disciplinary effort, ranging from the water-energy-food nexus to climate change. The WRC has a dynamic workforce, and a strong capacity building culture. Before the COVID-19 pandemic, more than 60% of new WRC project leaders were from designated groups, with over 450 students funded in these categories. The inclusion of bursaries for students is vital in for growing the next generation of researchers. The WRC publishes a professional academic journal, ***Water SA,*** indicative of the quality of South African water research, and takes water knowledge widely into the water sector through the ***Water Wheel*** magazine.

To appreciate the role that WRC has played in generating and applying knowledge in the wise use of water resources, we must acknowledge the relatively short period of time over which these advancements have been made. In only five decades, the institution has generated world-leading knowledge, and has become a flagship for change.

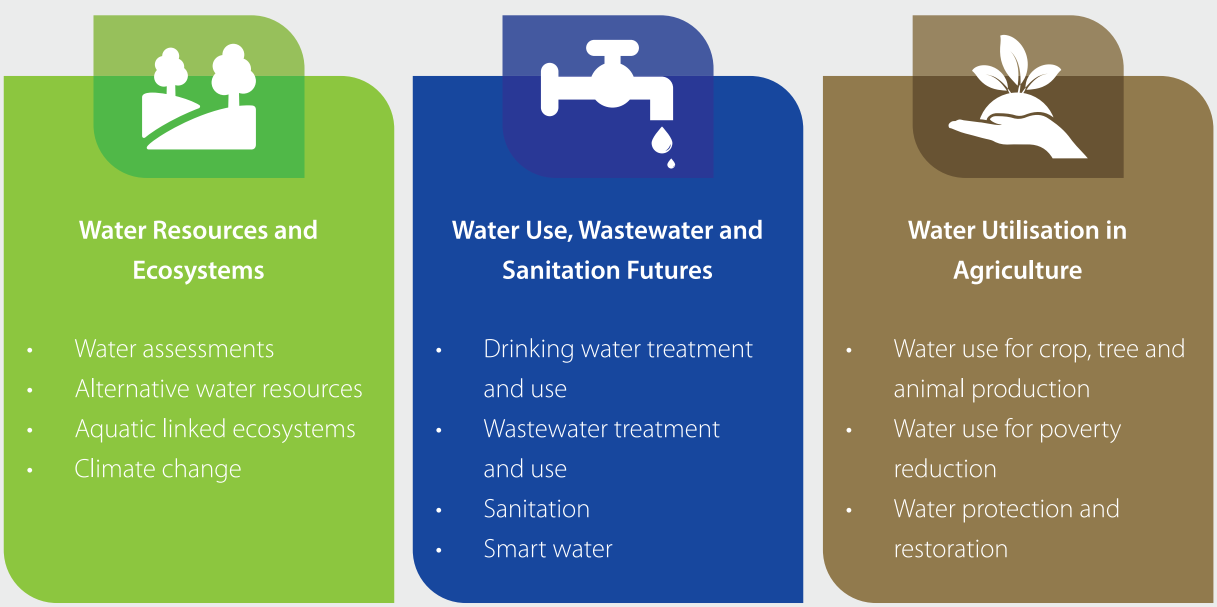
The new South African democracy ushered in many firsts. The first Catchment Management Agency (CMA) was established in 1996; the Water Services Act (108 of 1997) and National Water Act (36 of 1998) were promulgated; the National Water Resources Strategy was published in 2004, updated in 2014, and is currently under revision. From the start, the WRC has supported fundamental, imaginative research with potential for ground-breaking advances: from cloud-seeding, drip-irrigation and membrane technology to aquatic ecology and eco-toxicology. When challenges arose, research results were there to support responsive innovation.

Research on Water Use and Wastewater

Water is a fundamental driver in the economy, with no economic sector able to deliver national benefit without it. Water use includes the consumption of water, and the use of water to dilute and transport waste. In a water-scarce country the challenge has been to achieve maximum positive outcome with minimum use of water.

Water in mining and industry: The greatest research advances have been made in ameliorating the effects of water-use for dilution and waste disposal. WRC-funded research has taken South Africa to the global forefront of membrane technology, which is also applied in desalination to augment water supply. Acid mine drainage (AMD) remains a critical threat – with

Figure 1: The three business divisions in the Research and Development branch of the WRC.



research advances addressing treatment technology, as well as engaged research with communities affected by AMD.

Water in homes: Drought and geographically uneven rainfall have driven the great engineering feats of large dams and inter-basin transfers. These schemes have assured water supply through severe droughts, and into remote corners of South Africa. Secure water supply then required the development of far-reaching reticulation. The South African national government water slogan of the late 1990s was ***Some for all forever*** – indicating the commitment to water equity and sustainability for people and the environment. In the 2020s the slogan is ***Water is life, Sanitation is dignity***. Sanitation research is diverse and imaginative, allowing for solutions that range from dry sanitation and low-flush technology to the innovative best practice tool: Wastewater Risk-Abatement Planning (W_2RAP).

Water quality: The WRC has supported many facets of solving water quality problems. The development of complex multivariate water quality models, some of which can be linked in real time to hydrological models, means that complementary flow and quality management is possible. A comprehensive understanding of natural water quality of South African freshwater ecosystems sets benchmarks against which to measure deviations resulting from pollution and allow for quantified water quality guidelines. The concept of risk-based guidelines has recently been tested and adopted. Environmental water quality – managing water quality for ecosystem health – has been advanced through research on natural water chemistry, bio-monitoring, and eco-toxicology. Technological advances such as polymeric carbon solid technology are being tested to more effectively treat wastewater sludge. The WRC Roadmap for Development and Innovation (RDI) is leading the way in technical innovation. In the management domain, the innovative Blue Drop (water treatment works management) and Green Drop (waste-water treatment works management) processes are public accountability mechanisms developed to encourage voluntary best-practices.

Research on Water Utilisation in Agriculture

Efficiency: Agriculture uses the highest proportion of available water in South Africa, supporting national food security and a substantial export industry. The most fundamental advance is enabling decreased irrigation water-use while growing the agricultural sector. Efficiencies have been achieved through scheduling models, water-delivery technology, the development of drought-tolerant cultivars and varieties, and quantifying water-use by different crops. Rangelands and grasslands support the livestock industry and research has tackled landscape rehabilitation and understanding the water-use of natural vegetation. Agricultural research has also grappled with intractable, ongoing problems like soil salinisation, the control of agricultural pollutants (both toxicants like pesticides and nutrients like fertilisers) and the control of livestock pests like blackfly.

Food security: Hunger remains a challenge, with widespread poverty in South Africa, especially in rural areas. The trends of democratised landownership and emerging farmers have been supported by model development for smallholder schemes, as well as research on sustainable pathways to relieve poverty, hunger, and malnutrition among rural communities. Widespread and effective product-to-consumer cycles are being investigated. Funding for research in the water-energy-food (WEF) nexus is emerging.

Research on Water Resources and Ecosystems

Assessment: The WRC has nurtured the emergence of world-leading hydrology and hydrological modelling. This is the backbone of effective water resource assessment and management. The strategic value of accurate and effective resource assessment supports planning for development and economic growth. We face an increasingly unpredictable water-future in which we will depend on improved modelling capabilities, and the skills of uncertainty analysis. These are particularly important for managing the effects of climate change.

Ecological infrastructure – the natural capital of aquatic ecosystems: The 1980s brought an accelerated interest in aquatic ecosystems to the WRC. Early breakthroughs contributed an understanding of the effects on river biota of inter-basin transfers, the downstream effects of dams, and testing theories of river structure and function. Linking understandings of the hydraulic habitat requirements of riverine organisms to physical geomorphology and flow, laid the foundations for the world-leading South African research and method-development in environmental flows. There was a deep focus on rivers, but research on wetlands also flourished.

Policy and practice: WRC-funded research resulted in reliable environmental flow and environmental water quality requirement methods that were a prerequisite for pioneering a legal right of the environment to water. The fundamental understanding that people depend on ecosystems underpinned the link between sustainability and equity in South African water policy and law. It remains crucial to effectively communicate fundamental understandings of aquatic ecosystems to water policymakers and resource managers.

Relevance: In a digital, technical and urban culture, the dependence of people on ecosystems is not easily apparent. However, as climate change disrupts natural cycles, the fragility of human systems becomes more evident. The WRC investment in integrated catchment studies began the process of linking knowledge of people with knowledge of ecosystem function. Although the WRC no longer supports programmes like the influential Kruger National Park Rivers Research Programme, such initiatives produced some of the country's leading water thinkers and practitioners, like World Water prize-winner Dr Jackie King.

Water governance: It is not enough to know how water-systems work, whether they are infrastructure systems, ecosystems, societal systems – or the complex systems that include all of these – it is essential to understand and engage with the political and economic processes through which they are governed and managed. The WRC has responded by moving decisively into supporting water governance research. Wise water-use and good water governance remain key challenges of our time.

Social learning: Human well-being is going to depend more and more on adaptability – which is dependent on learning. The WRC is bringing research on social learning to bear on new mechanisms and pathways for transformation. We need to learn how to sustain healthy ecosystems and move towards societal equity, while remaining economically viable.

Representation, transformation and capacity building

In the early years of the WRC, staffing was demographically narrow, and support for institutional recipients was exclusive. Restructuring in the early 1980s brought in new people, and transformation of the executive began with the first women joining the executive committee in 1995. Since 2002 the WRC has collaborated with government to recognize the role of women through the ***Women in Water*** awards. Now, the full range of Higher Education Institutions are supported, as well as national entities like the CSIR, and NGOs. South Africa's rich diversity is reflected in the demographic profile of WRC staff, project research teams and students, with strong elements of reform and redress. WRC-led initiatives for accelerating transformation across the South African water sector include FETWATER (Framework Programme for Research, Education and Training in the Water Sector) and WIN-SA, which is a network of organisations focusing on improving knowledge sharing in the water and sanitation sector that targets local government and decision-makers.

The Water Research Commission: positioning South Africa to adapt into the future

At the same time as we celebrate the past 50 years, we grapple with the challenges of the present and future. Here are three strands of influence the WRC needs to navigate:

A global explosion of misinformation and a reduced trust in 'expert knowledge'

'Fake news' proliferates and solid research-based knowledge is discounted: This is evident in climate-change debates. The internet provides people with the most rapid access to knowledge in human history. But the internet is seldom quality-controlled and, critically, it has become a knowledge supermarket that distances knowledge-production from where it is used to make decisions and to choose behaviours. Ready access masks the real origin of sound knowledge. Just as milk is on supermarket shelves, and water flows from taps, 'knowledge' pops up in Wikipedia and a proliferation of internet sites. Google is now a verb. Most people recognise that milk comes from cows, some people recognise that water is generated by the hydrological cycle and is delivered via aquatic ecosystems into pipes and from there into taps. But fewer people recognise that knowledge is generated by research – over long periods of time – and only then is accumulated into various repositories – most immediately, the internet. In the same way as cows need to be farmed, and catchment processes need to be cared for, research needs to be continually replenished, and the new knowledge channelled to address growing challenges. The WRC is a critical part of the South African knowledge economy, articulating and re-establishing the value of reliable knowledge, and developing pathways for effective mobilisation of knowledge into policy and practice. This links to the second strand.

An urgent call for research to have evident, and immediate, uptake and impact.
For more than a century, and certainly during the existence of the WRC, research has found its way into society via peer-reviewed publication – the quality control of excellence in knowledge production. That pathway has not always 'delivered' high quality knowledge to the point of uptake as readily as needed. There is an increasing call for knowledge brokers, and for researchers to make connections that better enable knowledge uptake, and therefore impact. A perception also exists of vast untapped reservoirs of knowledge that only need to be 'mined', with little need to invest in the generation of new knowledge. There are pitfalls here. The first is that knowledge needs to be contextualised to be relevant and readily useful, so surfacing existing knowledge should include new investment in a contextualising process. Then, reservoirs of existing knowledge are not infinite and new knowledge really must be continually added. Finally, tailoring too many research portfolios to immediate, short-term requirements weakens long-term investment in well-developed research areas that are crucial to future, and changing, needs. This links to the third strand.

Unprecedented uncertainty where experience is no longer a guide to the future.
The rate of change of many factors in the world is accelerating. With a water lens, this is evident in hydrology, where modelling depends on good historical records, which are not always available (see the Hydrology and Climate Change chapters). With changes in weather and climate patterns, uncertainty studies are at the forefront of research development. Understanding how complex systems function confers resilience, because we learn to expect the unexpected, we are alert of feedback, and we can respond adaptively to "black swan" events – when the outliers of probability become reality. Uncertainty is countered by resilience. We acknowledge that resilience can be negative as in resistance to needed change, and well as positive – adaptation in the face of negative change. Positive resilience resides in understanding interlinked social and ecological systems and can be recognised, protected and nurtured.

The Water Research Commission: enduring and exceptional characteristics

The legally protected process of using water tariffs to fund water research, ensuring constant renewal and effective deployment, of knowledge capital: The Water Research Act is of central importance. The Act ringfences a proportion of water tariffs for investment in knowledge creation. Research renews and expands knowledge capital and brings innovative perspectives and approaches. Ongoing research support in this manner requires that the water sector, particularly government, experiences WRC outputs and impacts as useful – both usable and used.

Researcher salaries: Across the world, WRC funding of South African water researchers is envied. Few funding agencies elsewhere include human resources costs in the way provided for by the WRC. By including salaries for non-tenured researchers, the WRC nurtures a reservoir of talent in a sector of critical and growing importance. The inclusion of salaries in research grants has also enabled a wider range of researchers, inevitably broadening the scope of research. Importantly, the scope includes drawing NGOs into research, enabling research

Through the years the WRC has brought Communities of Practice together through events such as symposia, workshops and dialogues. (Credit: WRC archives)

to catalyse ethical, knowledge-based development, and supporting the emerging recognition that social justice and ecological sustainability are fundamentally connected.

Acting as a hub that creates and maintains national and international Communities of Practice in water research and professional water practice: The WRC has several mechanisms and instruments that support and maintain a vibrant ***Water** Community of Practice* across South Africa, and internationally. At the national level these include Reference Group meetings where researchers, throughout their careers, experience encouraging, and often rigorous, review of their work. The relationships formed in Reference Group meetings are often enduring and increase knowledge resilience. It is noticeable, though, that the relationship between the WRC and national Department of Water and Sanitation has weakened. This may be an indicator that vibrant Researcher-DWS-WRC partnerships in conceptualising research needs and direction, are also less common. More recently, the WRC ***Water Dialogues*** contribute to wider networking and draw in the end-users of research outcomes. An encouraging development is the focus on international partnerships, and the increasing role of the WRC in international water research co-funding.

Professional managers well versed in both academia and practice: WRC research managers are central to the success of the organisation. The manager recognises and nurtures incoming early career researchers, informs established researchers of directions and trends – and holds the network of communication together. WRC research managers have traditionally held a challenging bridging role between academia and practice, ensuring high-quality and accessible knowledge-flow into the practice-based sector, including government.

Academic quality and accessibility: Through the process of peer review, WRC research has been reliably of a high academic quality. The impact factor of the WRC journal, ***Water SA,*** has steadily increased and is today amongst the most trusted and valuable water journals in Africa. Being open access makes the journal papers widely available to anyone with internet access. The WRC has also communicated knowledge about water to a wider audience, through ***Water Wheel*** magazine, training documents and the water heritage series.

The Water Research Commission: Opportunities for change

Silos: Co-ordinated and focused effort in specific research directions has taken South Africa to the forefront of many water-related areas. Today, there is an increasing imperative for integration. Despite adaptive restructuring of key strategic areas of research, and the introduction of lighthouses, WRC research remains essentially supported through recognised silos and would benefit from more decisive integration initiatives and transdisciplinary approaches. This does not imply that centres of excellence are undesirable, merely that efficient communication channels between them, and with external groups, are essential.

Multiple cycles of funding for a researcher or research group: Developing a research idea into a solid, experienced area of expertise often takes more than three to five years. In the past it was possible for a researcher or research group to continue developing research over multiple 3-year cycles. Now there must be at least a 3-year break before repeat funding to a particular researcher or research group, for a specific research idea or focus. The policy is understandable in terms of diversifying and spreading research funding, but in certain cases a longer period would sustain innovative intellectual property development and encourage the building of research capacity at a frontier of research development. Such extended support would naturally emphasise quality and delivery.

Rigour and bureaucratic overload: As in many organisations, overload of research managers and researchers alike has weakened attention to scholarly rigour and imagination. Burgeoning bureaucracy, tick-box monitoring and evaluation, and loss of critical thinking are a blight on management hierarchies in the twenty-first century. We are sorely in need of the refreshing notions of fun and a passionate love of water resources. Management methods that include participatory monitoring and evaluation, including reflection and learning are more effective than mindless tick-box checking.

Growing the national investment in research: South Africa's percentage of GDP dedicated to research needs to be higher. WRC activity and advocacy in the focus areas of innovation, business development, and partnerships are key in securing additional funding to disburse.

Innovation: Water is inherently both a public and a private good. Innovation is critical to both. Innovation for public good needs to be promoted, and the word 'innovation' should occur more routinely in the context of water as a public good – a commons resource. Despite South Africa being a signatory to the United Nations Sustainable Development Goals, the ***South African Water Research, Development, and Innovation (RDI) Roadmap: 2015-2025***, implemented from within the WRC, distressingly only speaks to themes related to water demand, supply and use, and not at all to sustainable water resources management and ecological infrastructure. Clever technology is an essential and primary focus of innovation for business development, but focusing on business and private innovation without considering sustainability will lead to a dead end.

The Water Research Commission: Three significant research thrusts for the future

Resource economics: The WRC needs a sustained strategic direction in ecosystem services and resource economics research. South Africa's leading resource economists should be connected into the WRC research system. Few directed calls for ecosystem service and resource economics research have gone out during the 2011-2020 decade. Over the same period, local government has collapsed and taken with it much of our water economy. If we are to begin a recovery process, we need to put ecosystem services, resources economics, and water governance together, in a transdisciplinary research effort.

Revitalisation of aquatic ecosystem research: We can never say that "we have done enough". Ecosystem functions are the beating heart of ecological infrastructure – and are certainly not sufficiently understood to underpin sound decision-making. The new generation of aquatic ecosystem researchers needs new skills. They must be trained to undertake rigorous scientific study ***and*** to connect their specific knowledge into problem-solving spaces. This combination of skills development cannot happen if we are not investing in the science as well as its application. In the era of climate change, as ecosystems adapt and change, new knowledge is urgently needed, and renewed investment in aquatic ecosystem research is essential.

Addressing the difficult problems: failing municipalities, rampant pollution, vanishing aquatic habitat: Water research and the management of complex water-related problems will need to draw the concepts of systems thinking, much of which overlaps with adaptive integrated water resources management (see chapter on Water Law). The most intractable problems have multiple causes, such as climate change, increase in water use, pollution and environmental degradation. Making progress with these problems requires a shared understanding, by all those affected, of the desired outcome. The research and user communities then need to work together to make achievable and consistent changes until the envisaged state is reached. An additional complexity inherent in the process is that the system is in a constant state of flux, so community observations, the data from multiple disciplines and the interventions by managers will change, often unexpectedly, from one day to the next.

Evidently, from the state of many South African water resources, resource management is not functioning at this level. To achieve this, we must coordinate all the best the WRC offers in terms of research, knowledge and public communication. This is the challenge for the WRC during the next half-century.

We need the full diversity of knowledge, effectively connected. We need to nurture relationships that courageously drive action. As we appreciate water-related crises as complex problems, and people living on planet earth as complex social-ecological systems, we can see the value of transdisciplinary research.

In summary, transdisciplinary research addresses difficult long-standing problems; respects, draws on, and co-creates the broadest possible range of knowledge: academic disciplines (including science, social science, arts and humanities) as well as experience and practice (including professional, technical, local, cultural and indigenous); and is undertaken with, for, society.

The really tough, persistent problems require multiple knowledges, ethically and intelligently integrated, through engaged research praxis. None of our critical water problems will be shifted with disciplinary excellence and research silos alone.

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ABBREVIATIONS

AAPSIA	All Africa Public Service Innovation Awards
ABR	Anaerobic baffled reactors
ACRU	Agricultural Catchments Research Unit
AIDS	Acquired immunodeficiency syndrome
AMBIC	Ammonium bicarbonate (protocol)
AMD	Acid mine drainage
AMR	Antimicrobial resistance
ARV	Antiretroviral
BBM	Building Block Methodology
BDA	Big Data Analytics
BDC	Blue Drop certification
BMGF	Bill & Melinda Gates Foundation
BMP-S	Biodiversity Management Plans
BNR	Biological nutrient removal
BORDA	Bremen Overseas Research and Development
BWMP	British Biological Monitoring Working Party
CCRHC	Coordinating Committee for Research on the Hydrological Cycle
CCWR	Computing Centre for Water Research
CEO	Chief executive officer
CERM	Consortium for Estuarine Research and Management
CFE	Cape Fold Ecoregions
CMF	Catchment management forum
CRA	Comparative Risk Assessment
CSE	Centre for Science and the Environment
CRD	Coordinating Research and Development (committee)
CROC	Consortium for the Restoration of the Olifants Catchment
CSIR	Council for Scientific and Industrial Research
DDT	Dichloro-diphenyl-trichloroethane
DEA	Department of Environmental Affairs
DEWATS	Decentralised wastewater treatment system
DRIFT	Downstream Response to Imposed Flow Transformations
DWA	Department of Water Affairs
DWAF	Department of Water Affairs and Forestry
DWS	Department of Water and Sanitation
DSI	Department of Science and Innovation
DST	Department of Science and Technology
EBMs	Effect-based methods
EBPR	Enhanced biological phosphorus removal
ECOSAN	Ecological sanitation
EDC	Endocrine disrupting compound
EFlow	Environmental flow
EFR	Environmental flow requirement
EIA	Environmental impact assessment
ELU	Existing lawful use
EONEMP	Earth Observation National Eutrophication Monitoring Programme
ESOC	Emerging substances of concern
ES	Ecosystem services
ET	Evapotranspiration
eWQMS	Electronic Water Quality Management System
FBIS	Freshwater Biodiversity Information System
FBW	Free basic water
FETWater	Framework for the Education and Training in Water
FRC	Freshwater Research Centre

FSM	Faecal sludge management
GAI	Geomorphological Driver Assessment index
GBDT	Gradient Boosting Decision Tree
GCM	General circulation model
GDC	Green Drop certification
GDE	Groundwater-dependent ecosystem
GDP	Gross domestic product
GIS	Geographical information system
GHG	Greenhouse gas
GWRC	Global Water Research Coalition
HCD	Human capital development
HDSF	Hydrological Decision Support Framework
HFSR	Habitat Flow Stressor Response
HIV	Human immunodeficiency virus
HRU	Hydrological Research Unit (of the University of the Witwatersrand)
IAP	Invasive alien plant
IAWQ	International Association on Water Quality
ICM	Integrated Coastal Management Act
IFRs	Instream flow requirement
IHP	International Hydrology Programme
IMESA	Institute of Municipal Engineering of Southern Africa
IPCC	Intergovernmental Panel on Climate Change
IUGG	International Union of Geodesy and Geophysics
IUWM	Integrated urban water management
IWA	International Water Association
IWQM	Integrated water quality management
IWR	Institute for Water Research
KNP	Kruger National Park
KNPRRP	Kruger National Park Rivers Research Programme
KZN	KwaZulu-Natal
MAR	Managed aquifer recharge
MUS	Multiple-use water services
NIWR	National Institute for Water Research
NPRP	National Precipitation Research Programme
IWRM	Integrated water resource management
KSA	Key strategy area
MAR	Mean annual runoff
MEAF	Millennium Ecosystem Assessment Framework
MDGs	Millennium Development Goals
NAEBP	National Aquatic Ecosystem Biomonitoring Programme
NATSURV	National Industrial Water and Wastewater Survey
NBR	National Building Regulations
NCCRP	National Climate Change Response Policy
NEMA	National Environmental Management Act
NEMBA	National Environmental Management Biodiversity Act
NFEPA	National Freshwater Ecosystem Priority Areas
NIWR	National Institute for Water Research
NMMP	National Microbial Monitoring Programme
NRF	National Research Foundation
NWA	National Water Act
NWMP	National Wetland Monitoring Programme
NWRS	National Water Resource Strategy
O&M	Operation and maintenance
PES	Present Ecological State
POPs	Persistent organic pollutants
POU	Point of use
PRB	Permeable reactive barrier
RDI	Research, development and innovation
REI	River-estuary-interface
RHP	River Health Programme
RDM	Resource directed measure
RQO	Resource Quality Objective
SADC	Southern African Development Community
SALGA	South African Local Government Association
SAM	Strategic adaptive management
SANBI	South African National Biodiversity Institute
SANCIAHS	South African National Committee of the International Association of Hydrological Scientists

SANITI	Sanitation Transformation Initiative
SANParks	South African National Parks
SanPlat	Sanitation platform
SANS	South African National Standard
SARA	Sludge application rate advisor
SASAqS	Southern African Society for Aquatic Scientists
SASS	South African Scoring System
SCS	Soil Conservation Services
SDC	Source Directed Control
SDGs	Sustainable Development Goals
SFD	Shit flow diagram
SFRA	Streamflow reduction activity
SFWS	Strategic Framework for Water Services
SISs	Smallholder irrigation schemes
SPATSIM	Spatial and Time Series Information Modelling
SRFA	Sanitation Research Fund for Africa
SUDS	Sustainable urban drainage systems
TBA	Transboundary aquifer
TMG	Table Mountain Group (aquifer)
UCT	University of Cape Town
UD	Urine diversion
UDDT	Urine-diverting dry toilet
UKZN	University of KwaZulu-Natal
UNFCC	United Nations Framework Convention on Climate Change
UNESCO	United Nations Educational, Scientific and Cultural Organisation
USGS	United States Geological Survey
UWS	University of the Western Cape
VEGRAI	Vegetation Response and Assessment Index
VIP	Ventilated improved pit (toilet)
VTI	Variable Time Interval (model)
W_2RAP	Wastewater risk-abatement planning
WASH	Water, sanitation and hygiene
WBE	Wastewater-based epidemiology
WEF	Water-energy-food nexus
WESSA	Wildlife and Environment Society of South Africa
WfW	Working for Wetlands
WHI	Wetland Health and Importance
WHO	World Health Organisation
WIN-SA	Water Information Network – South Africa
WISA	Water Institute of Southern Africa
WISH	Windows Interpretation System for the Hydrogeologist
WITS	University of the Witwatersrand
WR	Water resources
WRC	Water Research Commission
WSA	Water Service Authority
WSUD	Water-sensitive urban design
WSI	Water services insitution
WSP	Water safety plan
WUA	Water user association
WWF	World Wide Fund for Nature
WWTP	Wastewater treatment plant
YWP	Yellowfish Working Group

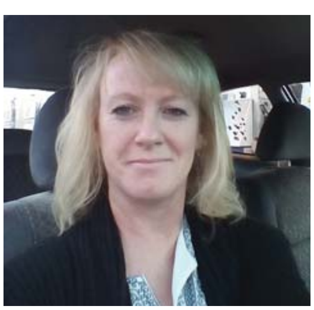
AUTHOR PROFILES

Albert T Modi – College of Agriculture, Engineering and Science, University of KwaZulu-Natal

Prof Albert Modi is the Deputy Vice-Chancellor for the College of Agriculture, Engineering and Science at the University of KwaZulu-Natal. He is a champion of sustainable agriculture, and of the value of indigenous knowledge in informing scientific research. Currently, Prof Modi is leading the uMngeni Resilience Project which is focusing on building resilience of small-scale farmers in the uMgungundlovu District Municipality, increasing yields, diversifying their produce and linking them to markets.

Amanda (Mandy) Uys – Laughing Waters Associates

Dr Mandy Uys attained her PhD in 1998 through the Institute of Water Research, Rhodes University. She is the Sole Proprietor of Laughing Waters & Associates (Aquatic Research, Consulting and Media), now in its 22nd year of operation in East London. She assembles multidisciplinary teams to provide specialist aquatic science services, specialising in biological monitoring; ecosystem evaluation and risk mitigation in developments affecting aquatic systems; environmental flows; and rehabilitation planning. She is also a science writer with a focus on water-related issues. Dr Uys is an open water swimmer, participating wherever possible in events which promote awareness of the state of rivers, estuaries and oceans. She is a member of the Southern African Society of Aquatic Scientists, Water Institute of Southern Africa, and Society for Ecological Restoration.



Belinda Day – University of Cape Town, Cape Water Consulting

Belinda Day received her degree from the University of Cape Town and joined the (then) Freshwater Research Unit. She began her MSc on palaeorelictual invertebrates but did an about-turn and became a domestic goddess for a number of years, whilst still keeping her toe in the freshwater world. She recently returned to the field and began an MSc in Conservation Biology. She plans to complete her MSc and combine her passions – conservation and freshwater ecosystems. Her special interests include the conservation and biogeography of freshwater ecosystems and climate change, as well as invertebrate identification, environmental education and writing popular science.

Bongani Ncube – Cape Peninsula University of Technology

Dr Bongani Ncube is a water and agricultural scientist based at the Cape Peninsula University of Technology. She has more than 25 years' experience in research and non-profit organisations. She started in the public sector in 1995, before joining the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) in 2000. She left in 2000 after obtaining a PhD with Wageningen University, The Netherlands. She then joined WaterNet, where she led the multidisciplinary Limpopo Basin Challenge Programme on Water and Food Project 17 until 2009. She migrated to the United Kingdom and worked for non-profit organisations for about 3 years. She came to South Africa in 2013 where she has been pursuing research on farming systems, water allocation, drought impacts on agriculture, indigenous knowledge, and water resource management. She is also a postgraduate supervisor and senior lecturer. She has produced more than 50 publications. She reviews for several international journals. She is also an Editorial Board Member of the *WaterSA* journal.

Carolyn (Tally) Palmer – Institute for Water Research and African Research Universities Alliance (ARUA) Water Centre of Excellence, Rhodes University

Prof Tally Palmer (BSc UKZN, Hons, MSc, PhD Rhodes University) is Director of both the Institute for Water Research, Rhodes University; and the Water Centre of Excellence in the African Research Universities' Alliance. Along with Silver and Gold medals from the Southern African Society of Aquatic Scientists, and a Women in Water award, she is a pioneer of engaged, transdisciplinary, sustainability research in South Africa. Her Adaptive Systemic Approach is designed to support transformations towards fairness for society and ecosystems (social-ecological justice). Tally's passionate research and practice spans aquatic ecology, water pollution, water governance and water resources management.

Christa Thirion – Department of Water and Sanitation

After matriculating from Hoërskool Douglas in 1982 Christa Thirion attained a BSc (Zoology and Mathematics) at the University of Port Elizabeth in 1985 and a BSc (Hons) on Limnology at the University of the Orange Free State in 1986. In 1987, she started work at the then Hydrological Research Institute of the Department of Water Affairs (DWA). While working she attained an MSc from the University of the Free State in 1998 and a PhD from the North-West University in 2016. The aim of her thesis was to determine the preferred ranges of water depth, velocity, temperature, and the substratum types required by Ephemeroptera, Trichoptera, Coleoptera and Diptera in South African rivers culminating in the Macroinvertebrate Response Assessment Index (MIRAI) v2. The MIRAI is one of a suite of Ecostatus indices developed as a collaborative effort between DWA and the Water Research Commission. Thirion is working as a scientist manager responsible for the National River Ecostatus Monitoring Programme at the Resource Quality Information System Directorate of the Department Water and Sanitation. She is the national

SASS5 auditor and has acted as associate Editor (Invertebrates) for the *African Journal of Aquatic Science*. She has authored and co-authored numerous scientific papers and technical reports dealing mostly with aquatic invertebrates and their relation to water resources management. In recent years she has focused mostly on mentoring and training junior scientists and the compilation of the annual National Ecological condition of Rivers reports.

Dhesigen Naidoo – Water Research Commission

Dhesigen Naidoo is a leader, a scientist and an activist for social change. He has, as CEO, led the Water Research Commission, South Africa's dedicated national water and sanitation innovation, research and development agency since 2011. He has previously served in senior positions in the South African national government and South African universities having begun his career as a medical scientist in a specialist paediatric hospital. He is also a Councillor of the National Advisory Council on Innovation and a Fellow of the Mapungubwe Institute for Strategic Reflection.

Donovan Kotze – Centre for Water Resources Research, University of KwaZulu-Natal

Dr Donovan Kotze qualified with a PhD in Applied Environmental Sciences from the University of Natal in 2000, with a thesis on wetland management in agricultural landscapes. Wetland ecology and the sustainable use of wetlands remain his focus and passion. He has gained much experience in working in a great variety of wetlands under many different land-uses, mainly in South Africa, as well as across eastern and southern Africa. He has worked extensively on the assessment of wetland ecosystem services and ecological integrity for a variety of purposes, including evaluation of rehabilitation projects and sustainability assessments.

Duncan Hay – University of KwaZulu-Natal

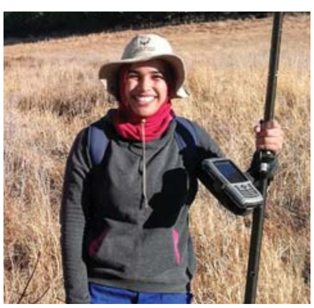
Duncan Hay is an associate research fellow of the University of KwaZulu-Natal and the retired Executive Director of the Institute of Natural Resources. He has an MSc degree in Zoology from the University of Natal and a post-graduate diploma in environmental security from the University of Cambridge. He has over thirty years' experience in natural resource management and rural development programmes and projects, and in developing the capacity of young professionals in these fields. He has led multidisciplinary teams to several awards, including a national Green Trust Award for the Eastern Cape Estuaries Management Programme (generously supported by the WRC). Duncan has authored over forty reports and publications, many of them focusing on translating technical subjects into a language that is understandable to the general public. Apart from directing the institute his recent focus has been on freshwater resources, particularly the role nature plays in water security.

Errol Malijani – Earth Sciences Department, University of the Western Cape

Errol Malijani is a PhD student at the University of the Western Cape, in the Earth Sciences Department, where she is undertaking research on a water quality related project. She graduated *Cum Laude* for both her Honours and Master's degrees and plans to continue growing her experience in the field of water quality.

Eunice Ubombo-Jaswa – Water Research Commission

Dr Eunice Ubomba-Jaswa holds a PhD in Microbiology from the Royal College of Surgeons in Ireland and an MSc in Medical Microbiology from the London School of Hygiene and Tropical Medicine. Her areas of expertise lie in microbiological water quality and how it ultimately affects public health. Dr Ubomba-Jaswa is currently a research manager: water resources quality at the Water Research Commission where she manages a portfolio of projects that deal with the thematic areas of source water pollution and human health, emerging contaminants (microbial and chemical), removal of contaminants as well as source water protection. She also supervises both PhD and MSc students registered in a number of universities in South Africa. She has co-authored over 30 publications which involve water research and sits on the editorial board of the international journal, *Integrated Environmental Assessment and Management*.



Faeeza Fortune – Stellenbosch University

Faeeza Fortune is a PhD candidate at the Department of Geography and Environmental Studies from Stellenbosch University. She holds a Master's Degree in wetland dynamics and remote sensing from the University of the Western Cape. Her PhD research focuses on understanding the fluvial morphodynamics of wetlands in semi-arid environments. Fortune adopts an interdisciplinary approach to her research by combining a variety of approaches in her study, including, spatial analysis using GIS, field and laboratory analysis, and numerical modelling of fluvial processes in valley-bottom wetlands.

Graham Jewitt – IHE Delft Institute for Water Education

Graham Jewitt is Professor of Hydrology at IHE Delft Institute for Water Education. Previously, he was Director of the Centre for Water Resources Research and Umgeni Water Chair of Water Resources Research at the University of KwaZulu-Natal. Over the past twenty years, he has led several water and earth system science-related initiatives, both in South Africa and abroad, with the relationship between land and water an overarching theme. He is on the editorial boards of

Hydrology and Earth System Sciences (HESS), *Global Sustainability* and *Water SA*. Recent work has been focused on the effective use of science to better inform land and water resources policy development, especially in developing countries, and developing tools to support the effective implementation of these. The nexus between water, food and energy and valuation of water resources with a focus on nature-based solutions are current research foci. He has authored or co-authored over 90 journal articles and supervised numerous PhD and MSc students from different parts of the world.

Helen Dallas – Freshwater Research Centre, Nelson Mandela University

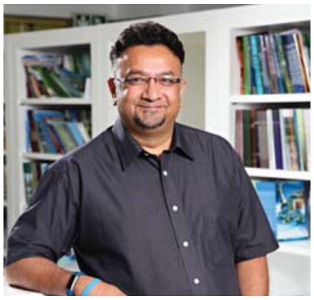
Dr Helen Dallas is the Director of the Freshwater Research Centre, a rated researcher (C2) at the National Research Foundation, and a Research Associate of University of Cape Town (UCT) and the Nelson Mandela University. She has over 30 years' experience working on and leading collaborative research projects on the ecology, conservation and management of aquatic ecosystems in southern Africa. She holds a PhD from the UCT and her work currently focuses on three core areas: 1) water temperature, climate change and aquatic ecosystems; 2) river health, bioassessment and development of biomonitoring tools in Africa, and 3) the development of biodiversity information systems for conservation, management and decision-making. Dr Dallas has published more than 50 scientific publications and serves as a reviewer for several journals and organisations.

James Machingura – Institute for Water Studies, University of the Western Cape

James Machingura is a biologist with a strong interest in freshwater ecology. He is fascinated by how biota, macro-invertebrates, in particular, in freshwater ecosystems respond to environmental and anthropogenic disturbances. His current PhD research work at the University of the Western Cape focuses on the development of biomonitoring and management tools to improve the monitoring and management of non-perennial rivers. He holds a Master's of Science degree in Entomology; as well as an Honours degree in Biological Sciences from the University of Zimbabwe.

Janine Adams – Institute for Coastal and Marine Research, Nelson Mandela University

Prof Janine Adams is a distinguished professor at the Nelson Mandela University. She is also Deputy Director of the Institute for Coastal and Marine Research and holds the Research Chair for Shallow Water Ecosystems, an initiative of the Department of Science and Innovation and the National Research Foundation. Her research investigates how blue carbon habitats (salt marsh, mangroves, seagrasses) respond to climate change, and explores ways to manage harmful algal blooms and improve coastal water quality. Outcomes apply across the science-policy-practice continuum and include actions to restore multiple ecosystem services to estuaries. She leads a team of over 30 researchers and works collaboratively with scientists from Australia, UK, France, USA, and east Africa. She has published over 170 journal articles, several book chapters, and many technical reports/policies. She is a fellow of the Royal Society of South Africa and in 2015 was awarded the Silver Medal of the Southern African Society of Aquatic Scientists for her innovative research and training of, to date, 35 Master's and 22 Phd students.



Jayant (Jay) Baghwan – Water Research Commission

Jayant Bhagwan is the executive manager of the Key Strategic Area of Water Use, Wastewater Resources and Sanitation Futures at the Water Research Commission, which focuses on the management of water and wastewater in the domestic, mining and industrial sector. He has been instrumental in creating the portfolio of research projects and innovations related to water supply and wastewater management. He completed his Master's Degree in Tropical Public Health Engineering from Leeds University, UK. With his knowledge and experienced gained in implementation of water and sanitation projects, he has played and participated in the shaping of national water policy and legislation. He has held the posts of the President of the Water Institute of Southern Africa, Chairperson of the Minister of Water Affairs and Forestry Water Advisory Committee, as well as international advisory positions with the Water Supply and Sanitation Collaborative Council, IWA- Global Development Agency and UNEP. He was among the global leaders who have pioneered the areas of non-sewered sanitation (NSS) and faecal sludge management '(FSM), and has been instrumental in the establishment of the Global FSM Alliance where he is one of the directors and the IWA specialist groups on NSS where he is the Chair.

Jenny Day – University of the Western Cape, University of Cape Town, Freshwater Research Centre

Prof Jenny Day is a freshwater ecologist with particular interests in invertebrates, wetlands and water quality. She taught in the Zoology Department at the University of Cape Town (UCT) for many years, 'retiring' in 2012, but still active in teaching, writing and research into South Africa's rivers and wetlands and their biotas. She has had a long history with the Water Research Commission, having been involved in one of the Commission's very first 'ecological' projects in the early 1990s. She is fortunate enough to live on the banks of Zeekoevlei in the southern suburbs of Cape Town.

Jody Reisenberg – Department of Biological Sciences, University of Cape Town

Jody is a PhD candidate in the Department of Biological sciences (UCT). Her research focuses on assessing the effects of rising water temperature on endangered freshwater fish. She began working with the Freshwater Research Centre in 2012 and has enjoyed contributing to freshwater conservation within the institution since. Jody is also an educator: she enjoys working with South African youth to increase representation in STEM fields for young women of colour.

John Ngoni Zvimba – Water Research Commission

Dr John Ngoni Zvimba is currently with the Water Research Commission as research manager responsible for the sustainable integrated wastewater management research portfolio. He holds a PhD degree in Bio-Physical Chemistry and has postdoctoral research experience in bioprocess engineering. His research areas of interest include sustainable municipal, industrial and mining wastewater management, focusing on beneficiation and volarisation. Dr Zvimba has authored/co-authored over 25 peer reviewed publications/book chapters, 1 book, 2 patents, several conference presentations and technical reports and supervised/co-supervised 4 MSc students and 2 PhD students. He is currently a member of the Water Institute of Southern Africa and International Water Association.

Julie Coetzee – Centre for Biological Control, Rhodes University

Dr Julie Coetzee completed her PhD at the University of the Witwatersrand in 2003 on the biological control of water hyacinth, which started her career in this field. She is currently the Deputy Director of the Centre for Biological Control at Rhodes University, where her research focuses on the biological control of invasive aquatic plants. Recently, she has shifted the focus of her work on floating aquatic plants to include submerged and emergent aquatic plants. As we have gained excellent control of the floating species, this new suite of species has taken advantage of these new habitats, threatening indigenous aquatic flora and fauna. Tackling these new problem plants is a challenge, but will benefit from experience gained elsewhere in controlling these species, as well as pioneering new methods of control for South Africa. The research conducted by Dr Coetzee's group of past and present postgraduate students contributes hugely to the management of invasive aquatic plants in South Africa and beyond our borders.

John Dini – Water Research Commission

John Dini holds a Master's degree in governance and public policy from the University of the Witwatersrand. He has over 20 years' experience within the South African public sector, working in the water and environment sectors. He is currently a research manager at the Water Research Commission, responsible for leadership of the water governance portfolio. Prior to this he was employed at the South African National Biodiversity Institute and Department of Environmental Affairs where he worked on policy development, international environmental conventions and law reform in relation to biodiversity and water.

Karl Reinecke – Southern Waters Ecological Research and Consulting CC

Dr Karl Reinecke has been working in the field of freshwater ecology since 2000, starting as a researcher in the Freshwater Research Unit in the Department of Zoology at the University of Cape Town, where he worked on two major research projects, first focusing on river restoration and then on the impact of woody exotic plant species on riparian zones. Thereafter, he joined Southern Waters to take on the role of a riparian botanist and since then he went on to complete his PhD in EFlows requirements for riparian plants. Karl has specialist knowledge in community ecology of riparian vegetation and in measures to mitigate the impact of water resource developments on rivers. He is also a specialist in aspects of physical degradation of rivers and mitigation thereof, impacts of riparian plant invaders, drivers of riparian community structure and riparian restoration.

Kate Rowntree – Rhodes University

Prof Kate Rowntree is currently Emeritus Professor at Rhodes University where she has mentored students and carried out research in fluvial geomorphology since 1986. Her research interests cover fluvial geomorphology, land degradation and integrated catchment management. She first worked on environmental flow projects as a fluvial geomorphologist in 1995 since when she and her students have been influential in developing relevant input into South African environmental flow methodology. She has been the lead researcher on seven WRC projects that have developed fluvial geomorphological tools relevant to environmental flow methodologies and was a team member for an eighth project. Her national and international contributions to geomorphology were recognised in 2019 through the award of a Fellowship of the Southern African Association of Geomorphologists.

Kate Snaddon – Freshwater Consulting Group, Freshwater Research Centre

Kate Snaddon graduated with an MSc in freshwater ecology from the University of Cape Town in 1998. She was mentored for all her years at the University of Cape Town by the inspiring Prof Bryan Davies, one of the freshwater 'originals' in South Africa! Her specialist skills lie in the areas of wetland and river ecology, freshwater macroinvertebrate identification and analysis, biomonitoring, wetland mapping and classification, conservation planning for the aquatic environment, and urban river and wetland management and rehabilitation. Kate is currently a consultant with the Freshwater Consulting Group, and a researcher with the Freshwater Research Centre in Cape Town.

Kevin Pietersen

Dr Kevin Pietersen has more than 25 years' experience in the water, environment, geosciences, and energy sectors. He has extensive knowledge in the exploration, development, and management of groundwater. He has worked on projects related to support for information systems, guidelines, decision support systems, prediction tools, technologies and methodologies that support protection of water resources and equitable allocation of water to meet the needs of the environment, social and economic development. He was the team leader for the Consultancy Services for Water Resources Management Research in the Eastern Kalahari Karoo Basin and Transboundary Aquifer and Big Data Analytics and Modelling: Localising transboundary data sets in the Southern Africa: A case study approach. He has worked extensively throughout Southern African Development Community. He holds a PhD degree in Hydrogeology.

Lara van Niekerk – CSIR

Lara van Niekerk specialises in the physical dynamics of estuaries; estuarine condition assessments; environmental flow requirements; climate change impacts on estuaries; and estuary management and policy. She led the team that assessed the ecosystem condition of all of South Africa's estuaries as part of the National Biodiversity Assessment 2018 and 2011. She played a leading role in defining the 'Estuary Functional Zone' and developing an 'Estuarine Ecosystem Classification'. Lara is the architect of the National Estuarine Management Protocol and drove the initiative and development of the generic framework for estuary management plans (GEF funded CAPE Estuaries Programme). She was part of the core team that drafted the 'Guidelines for the development and implementation of Estuarine Management Plans'. Van Niekerk is also part of the core team that develops environmental flow requirement technologies for South Africa, e.g. Version 1, 2 and 3 of the EWR methods for estuaries and been involved in over 40 Ecological Water Requirement studies. She led the project that developed the desktop assessment of South Africa's estuaries. Lara is author / co-author of 37 papers in national or international journals and more than 70 scientific reports.

Lerato Phali – University of KwaZulu-Natal

Lerato Phali is a PhD student in Agricultural Economics at the University of KwaZulu-Natal. Her research evaluates institutional integration, farmer participation and performance in smallholder irrigation schemes in KwaZulu-Natal, South Africa.

Liz Day – Liz Day Consulting (Pty) Ltd

Dr Liz Day graduated from the University of Cape Town with a PhD in marine biology, but changed salinities swiftly and has been working as a freshwater ecologist on rivers and wetlands for the past 24 years. She has a special interest in river and wetland rehabilitation and management, particularly in urban and agricultural areas.

Lulu Pretorius

Dr Lulu van Rooyen (nee Pretorius) holds a Bsc (Hons) in Plant Science (UP) and an MSc and PhD in Environmental Science (UNISA). She conducts research as a research fellow with the University of KwaZulu-Natal, works as a freelance environmental and ecological consultant, and is a director of a non-governmental organisation called the Centre for Wetland Research and Training (WetResT). She is a trained ecologist specialising in wetland ecology and management, with recent experience in climate change adaptation. She is registered with the South African Council for Natural Scientific Professions; belongs to various professional bodies; and is the current Chair of the South African Wetland Society (2019 - 2022).

Luxon Nhamo – Water Research Commission

Dr Luxon Nhamo is a research manager at the Water Research Commission of South Africa, and an Honorary Research Fellow with the University of KwaZulu-Natal. Dr Nhamo has over 20 years' of progressive research experience spanning three continents (South America, Europe, and Southern Africa). His areas of expertise include agricultural water management, GIS and remote sensing, water-energy-food nexus, climate change adaptation, and weather (early warning systems).

Maxwell Mudhara – University of KwaZulu-Natal

Prof Maxwell Mudhara holds a PhD degree in Food and Resource Economics from the University of Florida, Gainesville, USA. He lectures at the University of KwaZulu-Natal in South Africa in Agricultural Economics and Food Security. He is the Director of the Farmer Support Group, a community development, outreach and research unit at the university. His experience is in small-scale farming, research and extension, participatory approaches, and economics of smallholder farming systems and value chain assessments, food security analysis and project evaluation and impact assessment. He has been a team leader in many consultancy assignments involved in project formulation, monitoring and evaluation. Prof Mudhara has published more than 80 peer-reviewed papers in international journals and several book chapters.

Mohammed Kajee – Department of Biological Sciences, University of Cape Town

Mohammed Kajee obtained his BSc degree at the University of Cape Town in Marine Biology and Applied Biology in 2014. He then went on to complete his Honours degree in Marine Biology the following year. Kajee is currently working on his PhD focusing on the distribution patterns and trajectories of change for South Africa's freshwater fishes. Outside of his research, Kajee is particularly interested in issues of diversity and inclusivity, as well as finding effective ways to use education as a powerful tool to reduce societal inequality.

Nick Rivers-Moore – Freshwater Research Centre and Centre for Water Resources Research, University of KwaZulu-Natal

With a PhD in environmental hydrology from the University of Natal, Dr Nick Rivers-Moore undertook pioneering research on linking water temperature regimes to fish distribution patterns on the Sabie River. He has built up extensive expertise and professional experience as an aquatic ecologist working in river systems over the past 20 years, where he has authored/co-authored more than 50 peer-reviewed papers. His research interests primarily focus on the field of environmental hydrology, where he has applied his skills across disciplines, including freshwater conservation planning; climate change; ecological modelling; trout ecology; and catchment-level predictions of wetland occurrence, types and ecological condition. This has included research on water temperatures and flow patterns as drivers of habitat conditions to explain blackfly outbreaks in the Great Fish River (Eastern Cape) and the lower Orange River. Dr Rivers-Moore has applied this knowledge holistically at regional and national levels, where he successfully developed the first provincial freshwater conservation plan for KwaZulu-Natal, South Africa, and led a project to define areas of aquatic ecological importance for Zambia.

Nonhlanhla Kalebaila – Water Research Commission

Dr Nonhlanhla Kalebaila is a research manager at the Water Research Commission, leading a portfolio of research on domestic water supply, drinking water treatment and water quality. Dr Kalebaila possesses a PhD in Chemical Technology, specialising in water utilisation. During the course of her academic career she has worked in the fields of environmental science, applied science, biochemistry, microbiology, nuclear technology and water and wastewater treatment, and has authored and co-authored a number of peer reviewed research papers, including original research papers, a book chapter and conference articles.

Paul Skelton

Paul Skelton is a former managing director of the South African Institute of Aquatic Biodiversity and a freshwater ichthyologist since the early 1970s. After focusing on the fishes of the Cape at the Albany Museum he joined the JLB Smith Institute of Ichthyology (JLBSII) as Curator of Freshwater Fishes in 1984 and broadened his exposure to African freshwater fishes. Conservation of freshwater fishes was a second career path, and he pioneered the South African Red Data book for fishes in 1977 and again in 1987. In 1995, he became Director of the JLBSII and was instrumental in transforming the institute to a National Facility of the National Research Foundation in 1999. He retired in 2011 and returned to the study of freshwater fishes.

Rob Palmer – Nepid Consultants CC

Dr Rob Palmer is an aquatic scientist with a PhD in Zoology from Rhodes University. He has over 25 years' experience as a consultant with specialist knowledge of African rivers and wetlands, aquatic macroinvertebrates and freshwater fish. He has undertaken numerous environmental assessments throughout Africa, mostly concerning water resource developments and mining. He is a member of the South African Council for Natural Scientific Professions and an accredited SASS5 biomonitoring practitioner.

Rochine Melandri Steenkamp – Faculty of Law, North-West University

Melandri Steenkamp (LLB, LLM) is currently a Doctoral Candidate at the South African Research Chair in Cities, Law and Environmental Sustainability (CLES). She obtained her LLB in 2016 and her LLM in Environmental Law and Governance in 2018, both from the North-West University, Potchefstroom Campus. Melandri is a member of the Environmental Law Association (ELA), IUCN WCEL Climate Change Specialist Group and the IUCN WCEL Water and Wetlands Specialist Group. Melandri's research primarily focuses on urban law and governance, local government and its intersection with environmental, climate change and water law. For more information, see: https://orcid.org/0000-0003-3380-9087

Samkelisiwe Hlophe-Ginindza – Water Research Commission

Dr Samkelisiwe Hlophe-Ginindza is a natural scientist, passionate about water use and the conservation of this precious resource. She is currently with the South African Water Research Commission (WRC) as an assistant research manager responsible for the Water Use in Agriculture portfolio, where she manages the food safety and food security programme. She holds a PhD in Aquaculture with postdoctoral research experience in water quality, river health and research management. Her research areas of interest include sustainable water use in agriculture for sustainable livelihoods and agricultural water productivity. She has authored and co-authored several peer reviewed publications and several conference presentations. She received the WaterNet/WARFSA/GWP-SA Best Young Water Scientist Award twice.

Shawn Moorgas – Emanti Management

Shawn Moorgas is a municipal engineer employed with Emanti Management for the last 11 years. He brings extensive technical municipal skills to the team having operated as a Chief Engineer within local government for 11 years. His municipal background has equipped him with the necessary knowledge and experience for effective management of water, wastewater and solid waste operations. His unique understanding of the municipal environment has enabled him to provide technical support and appropriate turnaround interventions to municipalities in their efforts to achieve effective and sustainable water services management. In 2012/13, the Department of Water and Sanitation (Regulation) (DWS) appointed him as a Green Drop and Blue Drop Lead Inspector respectively covering water service audits in Northern Cape, Mpumalanga, Eastern Cape and Free State. He was subsequently appointed as a Blue Drop Progress Assessment Tool (PAT) assessor conducting evaluation and analysis of the 2013 PAT Reporting cycle in the North West and Western Cape. Moorgas also formed part of the development team of the WRC web-enabled Water Safety Plan and Wastewater Risk Abatement Plan tools and led the implementation thereof at selected municipalities in KZN and the Eastern Cape. These skills have led him to be part of a consortium to audit water and wastewater systems at the Department of Public Works and also provide mock audits and associated tool development for 19 wastewater treatment works operated by the Ekurhuleni Water Care Company (ERWAT). At the time of publication he was involved in two climate risk management projects for the WRC and the USAID water resilience programmes.

Sudhir Pillay – Water Research Commission

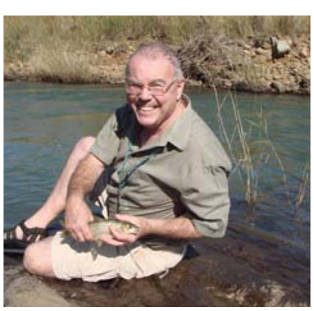
Dr Sudhir Pillay received his PhD in Chemical Engineering in 2012 from the University of KwaZulu-Natal, South Africa. As a postgraduate student, he won 3 scholar prizes from the Water Institute of Southern Africa and International Water Association (IWA) Young Water Professionals Southern Africa for his research on gravity-driven membrane technologies, anaerobic systems and decentralised wastewater treatment. He is currently employed at the Water Research Commission where he is responsible for the strategic moulding of the non-sewered sanitation research, development and innovation portfolio that has produced novel toilet systems, a scientific understanding of the thermodynamics associated with the drying of faecal sludges, and physical and biological-based resource recovery treatment options for faecal sludges. He is currently a member of the National Sanitation Task team, served on scientific committees for the IWA Peri-Urban Conference 2017 and IWA International Resource Recovery Conference 2017, represented South Africa for ISO standards development for Non-Sewered Sanitation, and part of IWA COVID-19 Task Force.

Stanley Liphadzi – Water Research Commission

Prof Stanley Liphadzi is a group executive manager at the Water Research Commission (WRC) and Adjunct Professor at the University of Venda. He leads the Research & Development Branch in the WRC in the production of new knowledge and Innovation in water and sanitation.

Stephen Lamberth – Department of Forestry, Fisheries and Environment

Dr Stephen Lamberth is a fisheries ecologist at the Department of Forestry, Fisheries and Environment (DFFE). He has been involved in about 30 specialist studies focusing on freshwater flow requirements / altered flows on river, estuarine and marine fish and member of the specialist teams developing the methodologies for estuarine flow requirements and assessing the freshwater requirements of the marine environment. He led the initiative assessing the impacts of altered freshwater inflows on marine fisheries, linking flow from the Thukela and other KwaZulu-Natal catchments on the offshore Thukela Banks prawn-trawl and traditional line fisheries. This work has been expanded to current projects assessing the links between flow and catches in amongst other, the small-pelagic (sardine and kin), demersal trawl (sole), squid and commercial and small-scale line and net-fisheries throughout South Africa's exclusive economic zone. Countrywide studies include a WRC project assessing fisheries production and economic contribution of all South Africa's estuaries and a comprehensive biological and socio-economic study of the nearshore and estuarine beach-seine, gillnet and commercial, small-scale and recreational line-fish fisheries. Outcomes of these projects, including the freshwater aspects, have been integrated into the work of the DFFE Fisheries Climate Change Task Team (FCCTT), in particular the vulnerability analyses and development of climate change mitigation and adaptation strategies for South Africa's marine and estuarine fisheries. Stephen is author / co-author of over 100 scientific publications.



Stephen (Steve) Mitchell

Dr Steve Mitchell, with qualifications from the Universities of London and the Orange Free State, brings over 50 years' experience in the sustainable management of natural aquatic systems. Starting his career as a limnologist with a particular interest in fish, he moved on to manage a trout hatchery and fishery before tackling the aquacultural conversion of livestock wastes for inclusion in stock feed. He was a research manager with the WRC on urban wastewater and then aquatic ecology. He retired in 2009, but continues to consult widely. He was President and Senior Fellow of the Water Institute of Southern Africa and directed various internationally-funded programmes, such as WARFSA and FETWater. He holds the Silver and Gold medals of Southern African Society of Aquatic Scientists.

Sumaya Israel – Earth Sciences Department, University of the Western Cape

Dr Sumaya Israel is a senior lecturer in the Environmental and Water Science section of the Earth Science Department at the University of the Western Cape (UWC), where she teaches and conducts research related to groundwater quality. Her undergraduate studies in Geology took place at UWC, while her Master's (2007) and her PhD (2015) was obtained from Stellenbosch University with a focus on groundwater remediation. She has about 20 years' of experience of working in industry where her research involvement has spanned over a number of topics, including Reserve determination, classification of groundwater resources, water quality assessments, monitoring network design, water quality monitoring, managed aquifer recharge research, characterisation of aquifers, site assessment for groundwater remediation, implementation of groundwater remediation, considering the spatial distribution and concentrations of various chemical constituents of groundwater in the environment. Her passion lies in understanding chemical processes linked to water rock interactions in various geological settings, as well as the influence of anthropogenic activities on these natural systems.

Susan Taljaard – CSIR

Dr Susan Taljaard is a marine, coastal and estuarine principal researcher in the Coastal Systems Research Group of the CSIR. Her research has been shaped by the CSIR's mandate to foster science that contributes to the quality of life of South Africa's people, and sustainable growth and development. Key areas of research include biogeochemical characteristics and processes in estuarine systems; development and application of integrated coastal management programmes and best practice guides; and development and application of policies and methods linked to the effective management of estuaries. These have been executed nationally, but also regionally in the Benguela Current Large Marine Ecosystem and the Western Indian Ocean. Her appointment as Adjunct Professor at the Institute for Coastal and Marine Research, Nelson Mandela University, offers her the opportunity to share her insights, and learn from the next generation of marine and coastal scientists.

Sylvester Mpandeli – Water Research Commission

Prof Sylvester Mpandeli is an executive manager at the Water Research Commission and Adjunct Professor at the School of Environmental Sciences at the University of Venda. He manages the Key Strategic Area that deals with Water Utilisation in Agriculture. His research interest is climate change adaptation, agricultural water management, food security and the water-energy-food nexus.

Tafadzwa Mabhaudi – Centre for Transformative Agricultural and Food Systems, University of KwaZulu-Natal

Dr Tafadzwa Mabhaudhi is an Honorary Associate Professor at the University of KwaZulu-Natal and Director (Acting) for the Centre for Transformative Agricultural and Food Systems, South Africa. His primary goal is to work on research and development that is dynamic, transformative, informs policy and achieves real-life impacts within poor communities. His research has evolved from focusing on crop water use and crop modelling to multi- and transdisciplinary research covering food systems, global environmental change, the water-energy-food nexus and the science-policy-practice interface.

Vimbayi Chimonyo – University of KwaZulu Natal

Vimbayi GP Chimonyo is a post-doctoral fellow working with the Centre for Transformative Agriculture and Food Systems at the University of KwaZulu Natal. She specialises in crop modelling (plant resource use), multicrop systems, crop production and seed technology. She has a passion for working with young scientists and smallholder communities. Her current research focuses on using integrated crop management to address food security issues, climate change, and rural development. Her main research interests are developing resilient cropping systems with an emphasis on sustainable intensification under climate variability and change.

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