DBSA Development Bank of Southern Africa

Development Planning Division
Working Paper Series No. 13

Challenges for human capital development and technological innovations in the South African water sector

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2009

Suggested citation

Karar, E, & Pietersen, K. 2009. *Challenges for human capital development and technological innovations in the South African water sector.* Development Planning Division. Working Paper Series No.13, DBSA: Midrand.

Note

This paper is one of a set of papers on the theme of water security that the Development Planning Division of the DBSA commissioned in 2009. There is a list of these papers at the back of this document.

Published by

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1. Introduction

"Knowledge is the engine that drives economic growth, and Africa cannot eliminate poverty without first increasing and nurturing its intellectual capital." Philip Emeagwali (2003)

There is a lack of human capacity in South Africa to assimilate the advances in science and technology necessary to deal with the complex interactions between the hydrological cycle and societal needs, while at the same time protecting the environment. It has been estimated that nearly half a million posts are vacant in the government or public sector alone (The Economist, 2008). In 2008, an estimated 1000 engineers, 300 technicians and 15 000 artisans were needed in order to reduce the national skills shortage (Mail & Guardian, 2008).

It is also recognised that each skilled and experienced water sector professional represents years of training and development. This begins with the person's early schooling and continues right through to postgraduate education and subsequent high-level job experience gained in specialist water-related fields. If this chain is threatened or broken at any point, the human potential of that individual may be lost or diverted elsewhere. This scenario is manifesting itself throughout South Africa and is potentially disastrous to the country's economic development.

This paper elaborates on the challenges faced in developing human capital and technological innovations in the water sector. Efforts to improve and transform water allocation and governance rest on a relatively small base of professionals in the water sector. The successful implementation of the state's water sector policy requires that this base should be broadened and strengthened as a matter of urgency.

An improvement in the rate of technological innovation in the South African water sector relies fundamentally on an increase in human capital. Unless skilled and talented people are attracted to the sector, technological innovation cannot happen. However, promoting technological innovation in water involves more than simply increasing the numbers of skilled professionals. Professionals should ideally cooperate in order to achieve a scientific or research "critical mass" which, in turn, will increase rates of innovation. Institutions should also be geared towards nurturing and encouraging innovation.

In addition, the regulatory and policy framework needs to be clear and unambiguous. If it is true that academic degrees in South Africa are "blind to the need for science, engineering and technology with an innovation outcome" (DST, 2008), then the causes for this deficiency should be addressed.

Over the past 35 years, research and development on behalf of the country's water sector has largely taken place under the leadership of the Water Research Commission (WRC). This has been done in accordance with its legal mandate. Research programmes and projects undertaken under the leadership and with the support of the WRC have been an indispensable training ground for the majority of professionals who have contributed – and continue to contribute – to the all-round success of the South African water sector.

1.1 Problem statement

South Africa needs more skilled people and new technologies to mitigate the challenges in the water sector. New water legislation in the country has triggered widespread reforms in the sector, demanding decentralised management and a shift from a supply-driven system to a demand-oriented paradigm. This comes at a time when the water sector is facing human capacity challenges, such as an ageing workforce, the emigration of professionals and constraints on university training. Put simply, the supply of skilled people is not keeping up with the demand.

There is currently a need for greater numbers of skilled water professionals entering and remaining in the sector. They should have better training, improved working conditions and clearer career trajectories.

1.2 The need for human capacity development and innovation in the water sector

Developing science, technology and technological capacity will generate knowledge. If well utilised, this knowledge will form the basis of good governance of water resources and will address most, if not all the urgent needs regarding water. Below are listed several reasons for the need for increased human capital development in the South African water sector:

- The continued implementation of water legislation requires sophisticated intervention measures, stakeholder consultation and decentralisation in the management of water resources to the lowest appropriate level.
- A focus on demand-side management approaches (such as water conservation, water reuse, rainwater harvesting, etc.) is needed in the light of the country's water scarcity, in order to reconcile water requirements with expected economic growth.
- Resource issues, such as climate change and the expected increase in intensity and variability of extreme events (e.g. floods and droughts), need to be dealt with.
- There is a need to manage water quality deterioration that can render water unfit for use and present a major threat to both human and environmental health.
- The lack of capacity, especially at municipal level, to operate and maintain water and wastewater systems has an impact on human health.
- The water infrastructure is ageing and will need to be replaced.

Water quality emanating from abandoned mines

Water quality problems are compounded in areas of abandoned, closed or liquidated mines. Pollution can include acidification, increased concentrations of salts such as sulphates, increased heavy metal pollution and increased erosion. It is estimated that there are approximately 8000 such mines in South Africa and that R100 billion will be needed to rehabilitate these abandoned sites. The abandoned sites are mainly associated with coal and gold-mining activities.

Water-treatment plants in a shocking state

"Small water-treatment plants across the country are being so badly run that the Water Research Commission has drawn up a manual to teach operators how to make their water safer. Conditions at some Eastern Cape plants are so bad that the deaths of dozens of babies in a diarrhoea outbreak last summer were blamed on poor water quality – despite earlier attempts to implement better systems. Some reports said more than 140 babies died in the outbreak in Sterkspruit and Barkly East" (Flanagan, 2008).

2. Mapping the human capacity problem in the water sector

2.1 Mathematics and science education in schools

A professional career in the water sector usually starts with a university degree in the natural, engineering or biological sciences (e.g. environmental science, engineering, biology or geology). These degrees usually have maths and physical science at matric level as an entry requirement. The shortage of teachers in these subjects at South African schools,[1] and the generally poor quality of education in these subjects, means that many school-leavers are automatically excluded from considering a science degree.

South African school curricula are currently being reorganised to focus on educational "outcomes". Efforts are being made to improve science and maths education in particular, but there is still a long way to go. Outcomes-based education also imposes additional requirements on teachers and may add to their workload. Many teachers welcome the change, but some are unable to adapt. Indications are that the teaching profession has some way to go before maths and science education challenges are met. It has been estimated that 25 000 South African teachers leave the profession every year, as against a figure of around 7000 new entrants (The Economist, 2008).

Mention must also be made of South Africa's legacy of apartheid education, the effects of which continue to be felt today. At a time when other developing countries such as China, South Korea and Taiwan were broadening their science and technological capacity, South Africa's economic plans

1 Some schools do not offer these subjects up to matric level.

deliberately excluded the majority of South Africans from scientific professions, as well as from most other higher-skilled professions.

University science departments face various challenges, but most agree that the lack of adequate entry-level skills in maths and science is one of the most serious issues: "No level of South African education, from kindergarten to post-doctoral studies, can yet be called a scientific success" (Christie, 2005).

2.2 Transformation in the science sector

South Africa's scientific research capacity is mainly white and male, which is predominantly a result of past bias. This situation needs to be addressed, albeit sensitively, as the challenge is to "square the circle" of retaining and even strengthening capacity while promoting transformation and representativeness. It is suggested that mentoring programmes need to be greatly strengthened and expanded, and proper recognition needs to be given to both the mentors and those mentored. There is little point in transformation if, at the end of the process, the net ability and capacity have been eroded.

2.3 Language as a barrier to entry

While South Africa recognises 11 official languages reflecting the linguistic diversity of the country, in practice most careers in the water sector will require competence in English. This will be either during tertiary education or in the workplace, and usually during secondary education as well. Most South Africans do not speak English as a first or even a second language, and the need to learn English probably makes it more difficult to gain access to these professions. This means that the advantages of mother-tongue education are not available to all South Africans. Better support to students and new employees who do not speak English as their first language is recommended, as is a move away from verbosity and "officialese" in reporting and other writing.

2.4 Emigration of skilled professionals – the "brain drain"

In January 2008, Fin24.com reported that at least 300 qualified engineers leave South Africa each year, and that 79 of the country's 231 local municipalities lack civil engineers, technologists or technicians (Mail & Guardian, 2008). As the global market for skilled professionals is growing, many South Africans are attracted by the opportunities and salaries on offer in other countries.

An expanding interest in the water and environmental sector globally has led to many jobs and some attractive career opportunities being created. Other, less positive reasons for the brain drain also exist, however. Concerns over South Africa's economy, the crime rate and the perception of weakening long-term opportunities result in many skilled people considering emigration.

2.5 Salaries and other inducements

Salaries paid to local water sector professionals are often given as a reason why many people leave the sector completely, or go to work in the private sector. In addition, career advancement means that professionals move into managerial positions and hence are lost to the technical skill, such as engineering.

While it is difficult to access figures to demonstrate this trend, it does appear that a professional leaving the public sector can double (or more than double) his or her salary on joining a private consultancy. This is partly a reflection of the competition between employers for skilled workers, but may also show an erosion – or a perception thereof – in the non-salary benefits available to public sector workers, such as pensions, holidays and on-the-job training.

While matching private sector salaries is difficult, public sector institutions could do more to publicise and formalise the benefits of working for the state. Talent retention is only partly about money – after all, few environmental scientists enter the profession to get rich. Job satisfaction is also a very important factor. At present, the "traditional" benefits of working for the state or a quasi-state organisation risk getting lost among various restructuring and reorganisational initiatives.

2.6 "Muddy" career paths

Careers in the water sector are often more difficult to describe than other professional careers, such as engineering, law or medicine. Few people know that jobs such as limnologist, hydrogeologist or aquatic biologist exist, or what these people do. Such careers are often perceived as less prestigious than long-established professions. There is, therefore, a need for the local and global water sector to publicise the careers that are available, and regulate them so that new entrants can clearly see how career progression can be achieved.

Porosity between disciplines also allows for greater mobility. Good initiatives in this regard include efforts towards professional registration and chartership, and the growth of learned societies and professional organisations. Mentorship is also important and has been identified elsewhere as a growing need. Unfortunately, science, engineering and technology professionals in South Africa can be described as "ageing and unrepresentative", according to the National Research and Development Strategy (NRDS) (DST, 2002). This is undoubtedly a problem in terms of the continued supply of mentors.

2.7 Unemployment among young science graduates

The phenomenon in South Africa of "large numbers of unemployed science graduates" (DST, 2008), particularly younger graduates, is likely to contribute to the decision by many school-leavers not to study science. In 2005, unemployment among graduates grew from 6.6% in 1995 to 9.7%. This translates into 36 000 jobless people with degrees and 165 000 unemployed holders of diplomas and certificates (Pauw et al., 2006).

This phenomenon is not easy to reconcile with the often-stated skills shortage in South Africa which deserves further investigation in itself, if negative perceptions of science are to be avoided. Questions such as these demand answers: Who are these unemployed university-educated scientists? What degrees did they study towards, and which jobs have they applied for? Why are they not getting jobs? What can be done to draw them into water-related professions? The issues of appropriate postgraduate degrees and funding opportunities are also important here. The following are some of the reasons given for the unemployment of young graduates (MacGregor, 2007):

- Graduates have qualifications, but do not always have the practical skills and experience
- The wrong types of graduates are being produced, as there are too few technical graduates
- Frequently graduates are not suited to filling shortages at managerial level
- Skilled staff members are often poached by other companies, or they emigrate
- Graduates are not always of a sufficiently high quality

3. Tertiary training: a cause for concern

3.1 University training in South Africa

There is no doubt that the state of university training in South Africa in the environmental science fields, including the water sector, is a cause for concern. Several factors are frequently cited as combining to challenge the goal of quality university education. These include increased teaching loads; more students experiencing problems with maths and science; poor academic salaries; the pressure to publish articles; and the reorganisation of universities.

Moreover, most university academics in technical fields have to do substantial amounts of private consultancy in order to augment their salaries. This has obvious implications for the amount of time they are able to spend with students. Private consultancy does bring benefits, such as exposing students to real-life projects and bringing in additional funding for research. Unless this practice is carefully managed, however, it can cause conflict with the primary task of supervising and teaching students.

Increased emphasis on targets and performance measurements in South African universities, or "managerialism", may also take their toll (Higgins, 2008). Traditional academic structures of authority have largely been replaced with a closer, hierarchical control of academics wielded by a "new class" of professional university managers. As a result, there is less emphasis on small-group teaching, less academic freedom, less dialogue and lower academic staff morale. Managerialism has at its roots a greater focus on financial efficiency than on academic outcomes.

While still controversial, these issues may have contributed to an increase in the numbers of vacant academic posts, with particular impact on the sciences. No doubt there are increasing numbers of vacant posts in university science departments. Although student numbers are increasing, it is difficult to fill lectureships, because the salaries are unable to compete with those in the private sector.

These conditions have forced engineering faculties to take extraodinary measures. For example: a high-level committee of three university deans of engineering was recently established in an attempt to stop the loss of university engineering academics (Mail & Guardian, 2008). A major issue identified by the committee has been the low academic salaries, compared with those in industry. Huw Phillips, Head of Mining Engineering at the University of the Witwatersrand, notes that problems in universities have a disproportionately large effect on the professions. After all, "one lecturer has the potential to graduate 50 to 70 students" (Mail & Guardian, 2008).

3.2 Examples for addressing the lack of capacity in the water sector

There are a number of current initiatives that support training and professional skills development in South Africa in the water, engineering and related fields. These are described below.

3.2.1 DWAF Learning Academy

The Department of Water Affairs and Forestry (DWAF) has established a Water and Forestry Learning Academy. The academy is a collaborative effort with universities and other training institutions that seek to draw young people into the water and forestry sector, and expose trainees to real-life work problems. It places a strong emphasis on mentoring by senior staff and on exposing trainees to a variety of specialist work areas by a process of job rotation. Funds are being allocated for bursaries for entrants to the academy, and professional associations are participating to ensure a focus on industry standards.

3.2.2 SAICE training courses

The South African Institution of Civil Engineering (SAICE) offers training in a variety of areas relevant to professional engineers, such as business finance, technical report writing and water legislation. SAICE supports continued professional development, as well as the development and updating of technical guidelines and documentation.

3.2.3 Eskom University

In recognition of the technical skills shortage and of the long-term business threat that this represents, Eskom is currently considering establishing a university to cater to its technical skills requirements. It is planning to spend R800 million per year on running the university. Speaking to SABC News, Eskom's Mpho Letlape said: "We just didn't want to miss any training that we ought to be doing, that we might not be doing, and assuming that it's happening in the business [sector]. That is why we went out and started the Eskom University" (SAPA, 2008). The planned university will coordinate and extend the organisation's current training programmes.

3.3 Summary

South Africa is faced with a capacity crisis in addressing its water challenges. This represents dire consequences for economic growth and development. In general, the skills shortage in the water sector can be attributed to the following factors:

- Poor mathematics and science education at primary and secondary school level, resulting in a reduced pool for further human capital development in the water sector
- Lack of throughput of suitable mentors to guide young professionals in their early career development
- Competition of various sectors for scarce skills, with the higher-paid professions being more attractive to young professionals
- Retirement, affirmative action and emigration

As with the energy sector, for example, there has been a lack of planning to address water management issues in the water sector. Numerous efforts are at play, however. Without leadership and the active involvement of the private sector to ensure adequate investments, as well as coordinated and targeted monitoring and evaluation, this problem will persist. Australia, for instance, is making huge investments in recruiting engineers and scientists from around the globe in preparation for their imminent water crisis, which is anticipated in the next 5–10 years. This human resource is crucial to fostering technological innovation.

4. Research: the role of the Water Research Commission

The way in which water research in South Africa has been structured ever since the WRC adopted a new strategic research direction in 2001, aligns very closely with the Strategic Framework for Water Services (SFWS) being proposed by the DWAF. For the purposes of effective management, the portfolio of research, development and innovation-related activities in the WRC is divided into five key strategic areas, namely, water resources management (WRM); water-linked ecosystems; water use and waste management; water utilisation in agriculture; and water-linked knowledge management.

In order to ensure that water research initiatives contribute effectively to addressing national development priorities and imperatives, this same portfolio of activities is refocused towards, and assimilated within, the following four integrating impact areas: water and society; water and the economy; water and the environment; and water and health.[2]

2 More information about the WRC, its strategic objectives, the way in which it operates, its complete research portfolio and products, is available at www.wrc.org.za and in the annually published WRC Knowledge Review.

4.1 Skills development: Scope of opportunity

Alternative ways of addressing skills shortages need to be investigated, for example rationalising the vast number of current water institutions. In addition, current programmes for building capacity should be continued. Much-needed programmes should be initiated to create new skills bases, with a special focus on firstly, the financial skills needed to understand long-term financial costs and the potential sustainability of water schemes and, secondly, groundwater capacity and skills for deployment in the DWAF and the catchment management agencies (CMAs).

4.2 Supporting research-linked initiatives

Over the years, the dynamic and constantly evolving research portfolio of the WRC has proved to be an excellent training ground for the majority of South Africa's water professionals. The number of postgraduate students participating in WRC projects provides a good indication of the extent of capacity building and skills development taking place. Based on 2007 information, about 580 students are supported annually by WRC projects, of which about 66% are from historically disadvantaged backgrounds. Approximately 60 research organisations are responsible for executing the research and providing the necessary mentorship for these students. These institutions are typically university-based groups, science councils, research consultants and non-governmental organisations (NGOs).

The nature of the research varies from fundamental (as done by some university groups) to highly practical and applicable (consultants and NGOs), and covers all the strategic research areas represented in the overall WRC research portfolio. Capacity building through participation in research has had a major positive impact on the performance of the water sector. For this reason, it is recognised as one of the WRC's key performance areas and will continue as a major component of the sector's suite of opportunities for skills development. Apart from the training opportunities provided by virtually all WRC-funded research projects, some projects are specifically aimed at skills development. The following are a few examples:

- Participatory development of training material for agricultural water use in homestead farming systems for improved livelihoods
- Development of training material for extension in irrigation water management
- Development of a comprehensive learning package for education on the application of water harvesting and conservation
- Development of a framework and model to regulate the competencies and training of managers and technicians in the provision of water services

5. Fostering technological innovation in the water sector

Innovation turns new ideas and scientific findings into "products, systems and services that people will either buy or use. The consequences of innovation are increased wealth and improved quality of life for all members of society" (DST, 2008). In addition to scientific skills, specific training in innovation may be needed.

An improvement in the rate of technological innovation in South Africa's water sector relies fundamentally on an increase in human capital. If skilled and talented people are not attracted to the water sector, then technological innovation cannot happen. However, promoting technological innovation in this sector involves more than simply increasing the numbers of skilled professionals. Professionals should ideally cooperate to achieve a scientific or research critical mass, in order to increase rates of innovation.

Institutions should be orientated so that innovation is nurtured and encouraged. The regulatory and policy framework in the country also needs to be clear and unambiguous with respect to innovation in the sector.

5.1 Public sector institutional structure and working conditions

Large semi-government research institutions, such as the Council for Scientific and Industrial Research (CSIR) or Mintek, have an explicit focus on scientific excellence and innovation. In South Africa, however, such institutions have difficulty retaining staff, as do employers in the private sector. The costs of advertising, interviewing and staff training are high. Part of this money would be well invested by carefully examining the reasons for poor staff retention, if only to bring down the costs of high staff turnover.

Too often, public sector managers blame staff turnover on high private sector salaries alone and fail to conduct exit interviews. The disadvantages of private sector work are often ignored, such as longer hours, job insecurity, commercial focus and less freedom to work on research. Although remuneration is important, water sector professionals are unlikely to be motivated solely by money. Public sector issues, such as convoluted bureaucracy, continual reorganisation, shifting management priorities and focus, poor recognition of technical staff, lack of adequate mentoring and political infighting, are not adequately acknowledged and addressed. Yet, these factors clearly contribute to low technical staff morale, both in South Africa and elsewhere.

5.2 Institutional coordination

Links between South African organisations involved in water policy and research could be greatly improved, particularly when considering large, multidimensional issues. Research organisations have to compete for research opportunities and funding, but this should not be at the expense of sharing data and collaboration when needed. Some South African institutions have suffered in the past (and in some cases still do) from a lack of research funding and the related need to show a profit in research. Frequently, it is a situation in which too many organisations compete for too little funding.

Given the relatively small numbers of specialists in each water-related field, this probably contributes to the problem of being unable to reach a critical mass. Some of the major water-related problems in South Africa (e.g. radioactive water in the Wonderfontein Spruit area near Krugersdorp) still lack truly effective cooperation between the different research institutions and universities with an interest or stake in the matter.

5.3 South Africa's private sector capacity

Unlike the United Kingdom and other countries, much of South Africa's leading water-related expertise (including its research capacity) lies outside of the public sector, which includes semi-public institutions, such as the CSIR and the Council for Geoscience (CGS). It is concentrated in private sector consultancies, as the state and its affiliates contract a considerable amount of work out to the private sector. Because these data and reports are seen as saleable assets, the consultancies are less likely to make them freely available to other researchers and organisations, in contrast to the practice by government departments or the national research councils. Private consultancies are also smaller than research institutions, which contributes to the problem of critical mass.

This problem is not confined to South Africa, but may be a growing phenomenon worldwide. The net result is probably poorer cooperation and a focus on shorter-term commercial outcomes over research publications. The answer is to make employment in state or semi-state institutions more attractive, not only by offering financial inducements, but also by emphasising traditional public sector strengths, such as security of tenure; better pensions; longer-term and more in-depth projects; etc.

5.4 "Unique" South Africa

There appears to be a conviction in parts of the South African technical community that local water issues are distinct enough from those elsewhere in the world to warrant a particular approach, and that South African hydraulic conditions are uniquely challenging. This is at least partly due to the isolation experienced by the local scientific community during apartheid. For example, with regard to hydrogeology, the CSIR (2008) states that "the complexities of groundwater management are particularly challenging in the southern African region because of its complex geology, fractured rock and a semi-arid climate, which differentiates it from the international norms".

These views, even if held only by a minority, may discourage vital international cooperation and collaboration. They may even result in instances of reinventing the wheel, so to speak, rather than producing true innovation. Linked to this situation are the ongoing legal and procedural difficulties experienced by foreign water experts in immigrating to South Africa. Indeed, "the country's present attitudes to skilled foreigners and to scientific immigrants may work against the chance of a prosperous future for South Africa in the era of globalisation" (Christie, 2005).

5.5 Clear signals from policy makers

For South African researchers to increase scientific innovation (i.e. scientific outcomes directed in innovative ways), clear directions are needed from policy makers as to the major questions that should be addressed. For example, is South Africa's surface water infrastructure in urgent need of repair or not? Are we dealing adequately with rural water supply and sanitation or not? Unfortunately, water can become a political battleground in which opportunities are taken to criticise government policy. It is, for example, argued by some that political interference in research threatens long-term water supply security (Farmer's Weekly, 2008).

The government is liable to respond by denying that the problem is as severe as portrayed. This can leave scientists wondering which problems need their attention and which do not. Signals from the government regarding science in general can also be confusing. For example, innovation and progress with respect to water and the HIV/Aids crisis (Ashton & Ramasar, 2002) have been affected by government statements on the topic that are at odds with the international scientific consensus.

5.6 The relative novelty of legislation

Much of South Africa's environmental legislation, including that which relates to water, is relatively new and is still being implemented. It may be that the scientific community will need time to digest the implications and outcomes of the legislation. They would have to see what direction public policy and enforcement will take before there will be any innovation.

6. Research and development support for technological innovation

The development of appropriate technology and the quest for technical innovation have formed the backbone of the WRC's research portfolio ever since the organisation's inception. As a result, the list of achievements in this regard is a lengthy one, including inter alia, the development and application of the following:

- Effluent treatment and water reclamation technologies and processes for municipal wastewater treatment
- A biotechnological system (BioSure™) for the joint treatment of mining and industrial wastewater and sewage sludge
- Rapid detection methodologies for pathogenic microorganisms in water

- Membrane technologies for the purification of saline water and wastewater
- Biomonitoring systems for rapid assessment of surface water quality
- Cloud-seeding technology for rainfall enhancement
- An integrated real-time rainfall monitoring and mapping system for real-time WRM and flood warning
- An in-field rainwater harvesting system for enhanced crop production
- Artificial groundwater recharge methodology for fractured hard-rock aquifers
- Desalination technology based on solar stills for the provision of potable water to small communities
- Software systems, sometimes used in conjunction with appropriate instrumentation, for efficient irrigation management
- Real-time flood warning systems
- Leak detection and water loss management systems
- Groundwater exploration and exploitation technologies
- Models for the prediction of land-use impacts on water resources
- Methodologies for establishing the environmental flow requirements of rivers

While continuing with research in support of the development of appropriate technologies, a large part of the WRC's research portfolio is aimed at achieving effective and sustainable management of complex, dynamic situations and systems. This is done for the joint benefit of society, the economy and the environment.

Water resource systems derive much of their complexity from natural hydroclimatic and hydrogeological variability. This inherent complexity is subject to further enhancement through external anthropogenic influences, such as climate change, changing land use and environmental degradation. Progress towards better management is dependent on developing a clear, quantitative understanding of the situations and systems to be managed.

This understanding has to be translated into decision tools that would support making the appropriate management decisions and choices. Many WRC research programmes and projects are consequently aimed at gaining a better understanding of complex, impacted, water-related systems. The objective is to develop appropriate measuring and decision tools for managing these systems effectively. Some of the current focus areas of such programmes and projects, as well as projects seeking to develop new, appropriate technologies, are discussed below.

6.1 Innovation and appropriate technology in water resources management

Numerical models are the main tools used to capture, package, communicate and utilise quantitative knowledge of complex and intricate hydrological and water resource systems. They are then used to simulate the behaviour of these systems in response to human manipulation or changing environmental conditions. The better a model is able to simulate the true, observed behaviour of a system, the better the level of understanding of the complex reactions and interactions captured in the model.

Good models can be used with confidence for many purposes. In water resource applications, it is most useful to explore the effects of different management options on a system, with a view to enabling correct management choices that would allow the system to behave in the desired manner. For this reason, the numerical simulation model is arguably the most appropriate of all technologies for managing hydrological and water resource systems in a sustainable and effective manner.

This also explains why so much innovative research effort is currently still directed at the improved modelling of hydrological and water resource systems. In fact, research not done within the modelling context is akin to doing research in a vacuum, with the danger of useful results being lost or overlooked. Besides seeking to improve models, modelling-related research may also aim at improving the quality of data and information that either describe system attributes or represent environmental or human system drivers. This is because the quality of such data directly affects the integrity of the simulated system response.

The current research portfolio reflects the ongoing focus on modelling-related innovation, aimed at consolidating knowledge and facilitating its beneficial use in the water resources and WRM arena. A major focus, for example, is on understanding and simulating the evaporation process quantitatively, and also on measuring evaporation for verification or "ground-truthing" purposes.

The evaporation process governs water losses from free water surfaces and soil, as well from different forms of vegetation and land cover through evapotranspiration or consumptive use. Accounting for these losses remains one of the weakest links in the modelling chain for water resources systems. Yet evapotranspiration, together with runoff, is key to quantifying the impact that land use variation and changes have on water resources.

Several research projects currently address the urgent need for models to produce the best possible evapotranspiration simulations. A research project focusing on the impact of deep-rooted trees on landscape evapotranspiration, for example, aims to reduce a major uncertainty in simulations of the catchment water balance. The ability to model evapotranspiration adequately is also a requirement for other current research projects. One of these studies aims to formulate methods and guidelines for the equitable licensing of stream flow reduction activities (SFRAs), which is a requirement of the National Water Act (NWA) (DWAF, 1998).

Some of the constraints to quantifying and modelling consumptive use of water associated with different land uses and agricultural practices are being addressed through remote sensing. For example, the use of hyperspectral imagery is being developed as a means of classifying and mapping land cover classes. This will enable measured water use to be more clearly associated with specific land cover types, thereby further enhancing modelling capabilities. Another example of remote sensing is the development of a methodology for estimating the soil water content of selected land areas, using satellite data. This not only helps to strengthen evapotranspiration and general water resources modelling, but also supports vital applications in drought monitoring, flood forecasting and catchment management.

Products of research projects that encapsulate hydrological and water resource research findings and information constitute valuable management aids. Current examples of such projects include a synthesis of hydrological research findings in a decision support system format for application in water resources planning and operations, and also a major update of the WRC's Water Resources of South Africa series of manuals.

6.2 Innovation and appropriate technology in groundwater and groundwater resource management

Distinguishing between groundwater and surface water often creates an undesirable, artificial division because, in reality, these are highly interdependent components of the total water resource system. This interdependency is in large measure not clearly understood and continues to be researched, thereby enabling management to optimise conjunctive use of surface water and groundwater. In other words, groundwater and surface water usage should be managed so that the one form of usage does not compromise the other and net benefits are maximised. One of the current research projects aims to develop a framework for optimising the monitoring of groundwater and surface water atmospheric parameters, with a view to enhancing decision making at a local level.

However, the detection, behaviour, assessment and management requirements of groundwater per se do differ from those of surface water in many respects. For this reason, the need for research with a narrower focus on groundwater, independently of surface water, persists. Current research aims at better understanding complex aquifer systems with a view to using and managing groundwater more effectively and sustainably.

Examples of such research include the following:

- Some projects deal with the conceptualisation of groundwater flows and the determination of storage and recharge characteristics in major aquifer systems, such as the Karoo and Table Mountain Group aquifers, on which communities are very dependent for their water supplies.
- Another project focuses more generally on the measurement of bulk flow and transport characteristics of selected South African fractured rock aquifer systems.
- New understanding of aquifer systems is continually feeding into research projects of a more applied nature, such as the identification and delineation of high-yielding, well-field areas in the Karoo and basement aquifers. These would serve as future water supply options to local authorities, and in support of rural communities in various parts of the country.

In the meanwhile, the search is constantly on for new methodologies for assessing South Africa's groundwater resources more accurately. An example is the development and application of a new methodology based on global navigational satellite systems.

6.3 Innovation and appropriate technology in water quality management

A thorough understanding of the complex processes involved would be the key to preventing the deterioration of water quality and the pollution of water resources. This, along with remediation, forms the cornerstone of water quality management that ensures that water resources remain fit for use.

Some 24 research projects are currently focused on generating new knowledge, or adding to existing knowledge. Their objective is to develop or refine tools and methodologies for dealing with critical threats to the quality of water in, or from, South Africa's water resources. Individually, each project addresses one or more of the following aspects.

6.3.1 Constituents responsible for deterioration in water quality

These include a range of salts; plant nutrients; heavy metals (mercury, in particular); light organic liquids (e.g. petroleum, affecting mainly groundwater); persistent organic pollutants (POPs); endocrine-disrupting compounds (EDCs); and pesticides.

6.3.2 Sources of constituents or pollutants related to water quality

These include both non-point (diffuse) and point sources, such as those associated with atmospheric deposition (air pollution); agricultural practices (both rain-fed and irrigation); gold and coal mining; various industries, including power generation; and sources associated with untreated or inadequately treated sewage.

6.3.3 Detection and assessment of pollution

Examples include the following:

- New detection methods and a bio-assay toolbox for EDCs
- A survey of POPs in the environment
- A national survey of the distribution and diversity of eutrophication-related toxic freshwater cyanobacteria
- A national survey of mercury levels in water resources
- The production of national sedimentation and sediment-yield maps

- A geographic information system (GIS)-based assessment of non-point sources of pollution
- More generally, maximising the value of water quality monitoring data and its benefit to users

6.3.4 Transport and fate of salts or pollutants

Examples include the transport and fate of:

- Light, non-aqueous (organic) liquids entering groundwater systems
- Salinisation associated with dryland agricultural practices, as salts are mobilised when natural vegetation gives way to crop production, specifically in the Western Cape
- Salinisation associated with irrigation practices and irrigation return flows
- More generally, at the catchment scale, contaminants associated with non-point sources of pollution.

6.3.5 Risk, impact and cost of pollution

Examples include projects that focus on the following:

- Modelling the cost of eutrophication associated with an excess of plant nutrients in water
- Assessing the toxicity of cyanobacteria produced by eutrophication-related blooms of toxic blue-green algae
- Developing and testing an EDC-associated framework for health risk assessment with a view to producing guidelines for controlling EDCs in drinking water
- Investigating the response of human immune systems to organic and inorganic constituents in water
- Developing a methodology for estimating the relative risk of pesticide contamination in South African water resources
- Establishing quantitative links between irrigation water quality and food safety with a view to providing irrigators with guidelines that could serve to protect the health of consumers
- Developing guidelines for the safe, sustainable use of greywater (water from a bath, basin, shower or washing machine) in small-scale agriculture and vegetable gardens.

6.3.6 Prevention and remediation of pollution

Approaches being investigated include:

- Effectively controlling irrigation-linked salinisation through appropriate irrigation management tools

- Considering the potential of methodologies for regulating dryland agricultural practices that cause salt mobilisation in cultivated areas and the salinisation of rivers draining those areas
- Removing nitrates that contaminate the groundwater being supplied to rural communities in certain areas
- More generally, determining the relative costs of pollution prevention versus pollution treatment or remediation

6.4 Innovation and appropriate technology in ecosystem management

Sustainable management of the country's water resource base is underpinned by innovation and the introduction of appropriate technology in aquatic ecosystem management. It is, however, dependent on first developing an adequate understanding both of fundamental ecosystem processes and of processes that underlie the delivery of ecosystem goods and services, particularly in the current context of demographic and climate change.

In the ongoing pursuit of better knowledge and understanding of ecosystem processes for the purposes of innovation, current research programmes address the full range of aquatic ecosystems, namely, rivers, wetlands, estuaries, impoundments and groundwater-linked ecosystems. Riverine processes have consistently enjoyed the most intensive study over the longest period. It has, therefore, recently become necessary to shift the focus more towards lesser-studied wetland and estuarine ecosystem processes.

Besides process studies, some current water-linked ecosystem research studies focus more directly on issues of ecosystem management and utilisation. Such research includes programmes and projects relating to ecological reserves; wetland and estuarine management considerations; ecosystem health; socio-economic considerations; and cooperative environmental governance. Innovative approaches and methodologies will be required in order to address these issues successfully.

The determining and setting up of an ecological reserve are key steps in the implementation of resource-directed measures (RDMs). These measures enable water resource managers to balance resource use with protection, and thus promote sustainability. Results of relevant investigations into methods of reserve determination and problems with reserve implementation are currently being consolidated into the second version of the RDM Manual (DWAF, 1999). The new update is expected to introduce much more stability into future operational applications of the reserve than is possible at present.

Meanwhile, research into reserve determination is continuing, with a specific focus on links to water temperature, as well as the requirements of wetlands and non-perennial rivers. The latter typically include tributaries of main rivers in the dry western parts of South Africa and even some river tributaries in the wetter eastern parts.

Knowledge of ecosystem health and environmental water quality provides the basis for developing tools that are used to balance resource use with resource health. The use of the resource, including the discharge of effluents, should be in harmony with the ecological health and sustainability of the resource and also with human health. Within this general topic, EDCs currently form an important focus of several research projects because of the threats they pose to the health of both aquatic fauna and water consumers.

6.5 Innovation and appropriate technology in the management of water in agriculture

Methods and tools for enhancing efficiency in irrigation planning and management that arose from past research are being taken through further stages of refinement and application, having already proved their substantial worth in practical situations. Specific projects in this regard include the following:

- Standards and guidelines are being compiled for the improved efficiency of irrigation water use from dam wall release to root zone application.
- SAPWAT and PLANWAT software is being integrated and upgraded to create a powerful, user-friendly irrigation planning tool.
- The soil profile wetting front detector is a low-cost, user-friendly tool that enables the user to apply irrigation water precisely according to the needs of the crop. It is being adapted for use in small-scale irrigation farming where water is applied via furrow irrigation. In addition, the detector is capable of sampling soil water on a regular basis. This research therefore also aims to realise the potential benefit of obtaining salt and nutrient measurements from soil water samples and interpreting them for management purposes.

In agriculture, maximising water use efficiency is about getting the most crop per drop of water applied. Advanced knowledge relating to the different crops' water requirements and best agronomic practices is an essential base from which to develop and refine tools for maximising water use efficiency in various soil and climate settings. Current research projects in this regard focus on intensively irrigated crops, such as sugarcane, pastures and orchards, as well as on drought-tolerant food crops (some of them indigenous) and crops for bio-fuel production.

The rural poor frequently can only obtain meaningful household food security if their basic water supplies and natural rainfall can be supplemented with additional water for gardening purposes. Rainwater harvesting heads the list of such technological options, and at least five research projects are being undertaken in this regard. They not only refine an already developed and proven technique, such as in-field rainwater harvesting, but also assess water harvesting techniques and practices in general for their acceptability and sustainability in different provinces and rural communities. As part of this assessment, a scoping study on indigenous water harvesting and conservation practices is also under way.

Smallholder irrigation schemes are generally intended to uplift the rural poor. The availability of water opens doors to irrigated subsistence agriculture, small-scale commercial farming and a range of other livelihoods for people on, and adjacent to, irrigation schemes. In researching and developing best-practice guidelines with a view to revitalising ailing smallholder schemes, performance criteria need to focus not only on achieving high crop productivity, but also on developing associated sustainable livelihoods.

Consequently, in addition to an ongoing focus on water use efficiency, crop productivity and the nutritional value of crops, a livelihoods approach is increasingly coming to the fore in the portfolio of research projects aimed at establishing best management practices for smallholder irrigation schemes.

6.6 Innovation and appropriate technology in domestic and municipal water management

In the domestic and municipal water sectors, technology development and innovation take place in the context of the increasing emphasis on assisting and equipping local government in the accelerated delivery of sustainable water and sanitation services and the general maintenance of water services infrastructure.

6.6.1 Technology for meeting environmental and regulation needs

Innovation in the arena of municipal wastewater management is being sought along a number of routes. A new research project is currently focusing on the pre-treatment quality of wastewater and how this can be influenced by the sanitation practice of urine diversion. If, as postulated, urine diversion results in an effluent which, after treatment, has much reduced nutrient and salt concentrations compared with conventional sewage effluent, this would provide the motivation for promoting this form of sanitation.

Several research projects are focusing on achieving more efficient biological nutrient removal from municipal wastewater. One novel approach is the search for indigenous *Anammox* bacteria. This would enable nitrogen removal via anaerobic ammonium oxidation to take place at a fraction of the total primary energy consumption of conventional nitrification processes.

6.6.2 Technology for ensuring good drinking water quality

In terms of technology for treating drinking water, research and development projects continue to investigate and develop innovative ways of enhancing the effectiveness of treatment plants. The focus is on the efficient removal of the more problematic constituents in raw water, as well as the efficient use of energy. For example, the provision of drinking water to coastal communities could eventually benefit from a research project that is investigating the development of a durable and reliable reverse-osmosis pump that utilises wave energy.

Treatment technologies that are particularly suited for use in small communities are receiving special attention. Many rural treatment plants fail to deliver water that meets drinking water standards. For this reason, priority is being given to producing a management tool that will consolidate appropriate knowledge relating to small-scale water treatment plants and facilitate their efficient operation and maintenance.

6.6.3 Technology for recovery and beneficial reuse

Research also seeks to broaden the beneficial use of sewage wastewater in the co-treatment of saline industrial and mining wastewater. A suite of technologies has been developed to supplement the hugely innovative BioSure™ process. Several other research projects also emphasise the use of municipal waste as a potentially valuable resource. In terms of energy production, a first-order estimate is being obtained of the quantity of domestic (and also industrial) waste available and the potential contribution this can make to satisfying national energy needs.

Sustainable methods and technologies for generating energy from wastewater are being documented. Other research projects continue to investigate the safe and beneficial use of sewage sludges as soil conditioners and plant fertilisers. A particular project is concerned with the potential of deep-row entrenchment of sludge derived from pit latrine and wastewater treatment works (WWTW) for forestry and land rehabilitation purposes.

As with drinking water treatment, many sewage treatment facilities for smaller communities can be classified as small-scale sewage treatment plants. An updated design manual is being researched for these facilities in the interests of good management and sustainability. Innovation focused on municipal water services (water supply and sanitation) is also being supported by various research projects, which are referred to later in this paper.

6.7 Innovation and appropriate technology in industrial and mine water management

In the industrial and mine water sector, the focus is on developing and promoting innovative management systems, appropriate technology and process improvements. These all support greater efficiency in the use of material and energy resources and thus help to reduce pollution. The development and improvement of waste and effluent treatment systems for environmental and human protection continue to be supported by current research projects. A stronger emphasis is also being placed on promoting the recognition of waste as a resource, and on the processes of waste recovery and reuse as commercial opportunities.

Currently, two research projects are concerned with quantifying water use and waste production in mining and industry. Five projects, in particular, seek to improve the ability to predict and quantify the impacts of water use and waste production. These projects are very important for deciding where to focus or refocus ongoing and future research investments aimed at innovation. Innovation is currently being sought in the following three main areas:

- Minimising the impact of waste on the water environment: This can be achieved mainly through the development and use of appropriate knowledge-based technologies and decision tools, as is being done in at least four current projects. These technologies and tools should guide the beneficial use where possible or, alternatively, the safe disposal of potentially detrimental or hazardous waste materials, including contaminated water and mining residues. A good example is the beneficial and sustainable use of neutralised acid mine water for irrigation purposes.
- Minimising waste production: This can be done through the development and use of more efficient or cleaner production technologies. Seven such research projects are currently under way. They focus, for example, on textile industry processes that substitute conventional chemicals with biodegradable chemicals; tools for minimising wastewater in multipurpose batch plants used for the sequential production of a range of products (e.g. pharmaceuticals); and various cleaner production tools for the mining, metal-finishing and petroleum-refining industries.
- Beneficiation in waste treatment: Beneficiation in treating industrial and mining effluents is the subject of more than seven current research projects. Included is the development of a suite of technologies for supplementing the Biosure™ process, thereby opening up beneficiation options for mining, industrial and municipal waste. A particular beneficiation step linked to Biosure™ currently under investigation is the recovery of sulphur from mining effluent. The recovery of metals from mine water is also being advanced by improving the reactor design to facilitate metal precipitation. Also under investigation is a novel technology for recovering water and solid salts from hypersaline brines, the disposal of which often poses a problem. The beneficiation of agricultural industry effluents is also under the spotlight as a means of gaining benefit from what might otherwise be a serious threat to water ecosystems.

7. Monitoring, targets and adaptive management

Recent research has underpinned the development, implementation and evaluation of several diverse monitoring systems dealing mainly with the state of South Africa's water resources. A few notable examples are monitoring systems focusing on the assessment of river health; establishing the microbial water quality of surface and groundwater resources; and producing maps of the daily rainfall over South Africa in near-real time.

Certainly, as far as water quality monitoring is concerned, research has been instrumental in target setting, especially in the form of water quality standards. Water management to ensure that social and environmental targets and objectives are met has frequently proved to be a highly complex undertaking. It was within this context that the concept of "strategic adaptive water management" was pioneered through research on the management of rivers in the Kruger National Park.

Current research projects continue to support the development of new monitoring systems, and either refine existing systems or extend their capabilities. Just as remote sensing has extended the daily monitoring of rainfall at sparsely distributed sampling points to continuous spatial monitoring over the entire country, so satellite measurements are contributing to the development of systems for continuously monitoring the moisture of catchment soil.

Together, new approaches to rainfall and monitoring of soil moisture create new opportunities for beneficial catchment management. These applications can be linked, for example, to water management, agricultural decision making, flood warning and drought monitoring. Remote sensing is also being investigated as a tool for monitoring the legal compliance of surface water and groundwater users in a catchment area.

The capability and cost-effectiveness of systems for monitoring water quality will further benefit from research projects focused on the following issues:

- Research on water service regulations and water tariffs
- Status quo studies on plumbing and water conservation devices
- Sampling and monitoring protocols for radioactive elements
- A national survey of mercury levels in South African resources
- The monitoring of drinking water quality
- New detection tools and techniques for the above
- The development and implementation of an EDC bio-assay toolbox and, more specifically, a non-sophisticated assay for EDCs
- The occurrence of POPs in the water environment
- The development of quality control and assurance guidelines for South African toxicity-testing laboratories
- An investigation into maximising the value of data on water quality monitoring for the intended users

Effective monitoring in support of sustainable development and the use of groundwater depends on a sound knowledge of water flows between interlinked atmospheric, soil, surface water and groundwater systems on a local scale. Different agencies have different interests and responsibilities for monitoring these various components. For this reason, an important cross-cutting research project aims to develop a framework for the optimised monitoring of the most important variables and practices for managing groundwater resources effectively. This will be based on an adequate understanding not only of the water flows, but also of the institutional and legal interactions of various responsible agencies.

A series of research projects concerned with the health of freshwater systems seeks to realise the full benefit of linking monitoring systems to adaptive management by setting appropriate targets.

One project seeks to strengthen river health monitoring through the development and incorporation of a diatom-based bio-monitoring protocol for South African rivers and streams. Another focuses on deriving conservation targets for freshwater systems. A third project aims to apply and test a strategic adaptive management system for freshwater systems in order to achieve targets associated with national water policy.

It is envisaged that, in future, more research attention will be given to developing appropriate institutional arrangements for sharing information and acting on the outcomes of monitoring and evaluation. This can be done by adjusting strategies and operations within a coherent strategic intent.

8. Conclusions

Various initiatives in South Africa are aimed at addressing the technical skills crisis. They are together discussed in the Science, Engineering and Technology Human Capital Development Strategy 2008-2028, developed by the Department of Science and Technology (DST, 2008). Examples include the NRDS, the National Skills Development Strategy (NSDS) and the National Plan for Higher Education. These initiatives, together with concrete actions, such as SAICE training courses, the DWAF's Learning Academy and the Eskom University, promise to do much to remedy the problem. Although the focus is primarily on encouraging South Africans to enter a science and technology career, there is still further scope for measures to attract foreign scientists and stem the emigration of local scientists.

In times of rapid environmental and demographic change, the chances of successfully taking up water management opportunities through "learning by doing" or "trial and error" approach diminish. By contrast, the need for a strategic, adaptive management approach based on proactive research increases. Managing water utilisation optimally for sustainable growth and development should therefore be seen as a highly dynamic process that needs constant research support. On the whole, however, the South African water sector is adequately served by its research arm through current research programmes and projects.

In closing, recommendations for the water sector include the following:

- There should be an awareness of, and support for, those initiatives discussed above and others aimed at growing skills in the sector.
- Established professionals in the sector should consider participating in mentoring programmes, if they are not already doing so. Such activities are now recognised as contributing to social responsibility programmes.
- Efforts to link individual scientists and their institutions should be supported, helping to establish critical mass in the sector.

- Efforts to understand and remedy the difficulties South African university science departments and their students face should be supported. It is likely that with further discussion a broad, sector-wide consensus on this issue could be gained, and communications with policy makers entered into from a common position of strength. Broader issues of relevance to university teaching, such as language competence, should also be considered.

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List of acronyms and abbreviations

Aids	acquired immune deficiency syndrome
CGS	Council for Geoscience
CMA	catchment management area
CSIR	Council for Scientific and Industrial Research
DBSA	Development Bank of Southern Africa
DPRU	Development Policy Research Unit
DST	Department of Science and Technology
DWAF	Department of Water Affairs and Forestry
EDC	endocrine-disrupting compound
GIS	geographic information system
HIV	human immunodeficiency virus
JIPSA	Joint Initiative on Priority Skills Acquisition
NRDS	National Research and Development Strategy
NGO	non-governmental organisation
NSDS	National Skills Development Strategy
NWA	National Water Act
POP	persistent organic pollutant
RDM	resource-directed measure
SAICE	South African Institution of Civil Engineering
SFRA	stream flow reduction activity
SFWS	Strategic Framework for Water Services
WRC	Water Research Commission
WRM	water resources management
WWTW	wastewater treatment works