Hydrological science in South Africa: 1995–1998

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This paper presents recent progress in the hydrological sciences in South Africa as reported to the International Association of Hydrological Sciences on a 4-year basis. It covers hydrology in its broadest sense, in terms of water quantity and quality, surface and groundwater, from both a scientific and a water management perspective.

Water resource management

Water resource management in South Africa is going through a period of major change. This is reflected in two new acts, the Water Services Act[1] and the National Water Act.[2] In line with internal political changes and international policy thinking, the country's new water policy and legislation have been founded on the principles of equity and sustainability. Major issues that had to be addressed are the 'water-stress' situation, given South Africa's semiarid climate and the present population level around 40 million, the very uneven distribution of water resources over the country and the entrenched inequity in access to and control over water resources.

Since the change in government in 1994, the highest priority has been afforded to community water supply and sanitation. The Water Services Act provides, in its initial stages of implementation, for a minimum of 25 litres of water per person per day within 200 metres of their homes, at a 'lifeline' tariff. The initial estimate was that 12 million people did not have ready access to safe water supply and sanitation. Since then, through various stages of learning and fast-tracking, for instance the use of private sector capacity in the BOTT (Build-Operate-Train-Transfer) approach, approximately 3 million people had been served with a minimum water supply by the end of 1998. Despite the success of delivery, there is concern about the sustainability of this approach, reflected, for example, in the very low cost recovery of these new schemes, to date only about 10 %. The strengthening of local government is the obvious long-term answer. There are also opportunities for the private sector as water services provider within the legal framework of the Water Services Act.

The National Water Act emphasizes the indivisibility of water resources, compared to the past situation where groundwater was regarded as 'private water'. National government will in future be custodian of all water resources, responsible for their protection and allocation. The main instrument in the Act to achieve equity and sustainability is the 'Reserve' — the water needed to supply basic human needs and to protect aquatic ecosystems in order to ensure ecologically sustainable development. Only the Reserve is a right to water in law: all other uses of water are authorized according to the criteria of public interest, equity, efficiency and optimal utilization.

The new water policy[3] has also shifted the emphasis away from the traditional water supply management to water demand management and ways in which water can be conserved in each user sector. A 'National Water Conservation Campaign', initiated in 1995, has already had considerable impact with demonstration projects such as water-saving devices, informative billing systems and school water audits. The complementary 'Working for Water Programme' has caught the imagination of the general public, because of its multiple benefits and rapid countrywide replication. Launched in 1995, the programme today employs over 40 000 previously unemployed people to clear catchment areas of invasive alien plants to conserve stream flow.[4]

Water management will be devolved to 18 catchment management agencies that will have to be established over time. All significant water use will be charged for, regardless of where it occurs, including the use of water resources for effluent disposal, and activities that reduce runoff with a detrimental impact on downstream water users. Charges are to promote efficient use of the resource and should cover a realistic portion of the water management costs.

The National Water Act for the first time also stresses national government's responsibilities with regard to monitoring, resource assessment and a national information system in support of decision-making. Information on the status of water resources, factors affecting water resources and present and future demands on water resources, must be readily available, not only to national government and to water management and planning agencies, but also to stakeholders and the public. Besides the traditional hydrological monitoring systems, a national river health assessment programme is presently being implemented countrywide.

The new policy in South Africa calls for much more integrated management of all water resources than in the past. The new management approaches have major implications for hydrological information requirements as well as for the future hydrologist. Our understanding of hydrological processes will have to grow considerably, both at the local and regional scale. The hydrologist will have to move beyond his present role of resource assessor to one of practical manager of the hydrological cycle.

The Reserve, both in concept and in its quantification, presents a major challenge to the hydrological community. Besides the river channel, the interface parts of the hydrological cycle, for example areas of infiltration, groundwater discharge and water use by riparian and terrestrial vegetation, have become focus points in the assessment of the ecological reserve.

Armed with his wider understanding of the hydrological cycle, the hydrologist also needs to play a stronger practical role in water service provision. Appropriate technology with full community participation, for example spring protection, rainfall harvesting, artificial recharge and agroforestry, should be harnessed to optimize water use and conservation at plot and small-catchment level.

The effect of the above water resource policy changes is already starting to be felt in hydrological science practice in South Africa, as reported in this article.

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Surface water

Water is arguably South Africa's most precious natural resource. Our groundwater resources are relatively meagre, therefore South Africa's major water supplies are and will probably always be derived mainly from surface water. The climate of South Africa is semiarid, with an average annual rainfall of 475 mm, compared with, for example, 735 mm for the USA and 860 mm for the world. For the country as a whole less than 9 % of rainfall reaches the river systems as runoff. Total runoff for South Africa is a mere 51 billion cubic metres on average.[5] This places the country close to the threshold of 1000 persons per million cubic metres of flow per annum, used to indicate countries that are water-scarce.

Water resources development

The erratic flow regimes of most of South Africa's rivers has led to the construction of many dams in order to harness the water resources. Growth in reservoir construction was extremely rapid in the second half of this century. In 1950 total storage capacity was about 3 billion cubic metres, but this has since grown tenfold to the present figure of about 30 billion cubic metres. The total volume of water stored in these reservoirs can be used as a barometer to indicate the overall status of our water supply system at any time.[6] For example, when the total volume in storage drops below 50 % of capacity there is cause for concern, whereas a condition of 90 % full is considered to be highly satisfactory.

A review of the last three years

As 1995 drew to a close, most of South Africa was still suffering from severe drought conditions that had persisted since early 1992. This drought had the effect of depleting total reservoir storage to well below 50 % of capacity. It can be seen from Fig. 1 that the volume dropped to 37 % of capacity by the middle of November 1995.

South Africa often sees droughts broken in dramatic fashion — a typical feature of our erratic climate. This phenomenon is clearly illustrated in Fig. 1, which shows a rapid rise in storage to reach 84 % by the middle of March 1996. The 47 % increase represents a volume of about 14 billion cubic metres, which is about 28 % of the total country's mean annual runoff.

However, the increase in storage alone does not give the complete picture for the following reasons. First, less than half of South Africa's water resources are harnessed by dams and, second, many of the dams spilled huge volumes of water. For example, Vaal Dam started spilling on 1 January 1996, after being at 13 % at the beginning of November 1995. The volume spilled in the ensuing two months could easily have filled another dam as large as Vaal Dam. As a result of the spillage, which was supplemented by high flows in its various tributaries, the Vaal River was in flood for several weeks. Flooding was also experienced over much of the summer rainfall area. Typically, runoff for the 1995/96 season was of the order of two to three times the long-term average.[7]

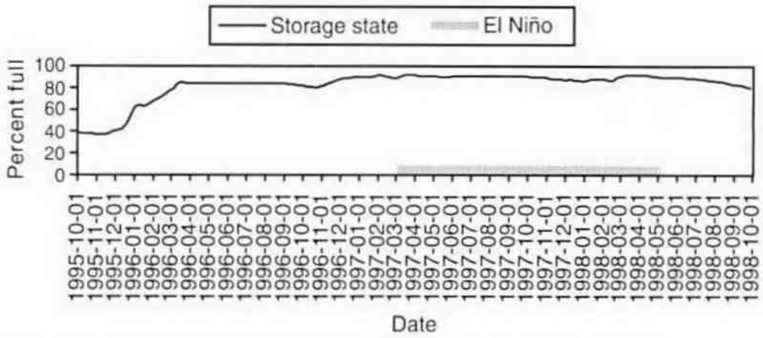

Fig. 1. State of reservoirs in South Africa (October 1995 to September 1998).

As can be seen in Fig. 1, the high storage state was maintained throughout the winter of 1996, falling to 80 % in October of that year. Good rains in the 1996/97 season saw the percentage capacity rise to over 90 %, falling to about 86 % by the end of 1997. Storage again passed the 90 % mark early in 1998, but declined more rapidly in the ensuing winter than was the case in the preceding two years, reaching 80 % by the beginning of October 1998.

What about El Niño?

The euphoria over the healthy status of South Africa's dams was quickly dissipated by extensive media coverage of the El Niño phenomenon. El Niño is used to describe the situation when sea temperatures in the eastern Pacific Ocean rise to above-normal levels. El Niño gives rise to unusually wet conditions on the eastern shores of the Pacific, coupled with dry conditions on the western fringe. Severe drought conditions were also predicted for southern Africa, since recent El Niño events tended to coincide with dry conditions in the subcontinent.

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The Southern Oscillation Index (SOI) — an accepted measure of the atmospheric component of El Niño — is based on the difference between monthly mean sea-level pressures at Darwin and Tahiti. Negative values of the SOI generally represent El Niño events. Figure 2 shows the variation of the SOI over the same period for which the storage states are plotted in Fig. 1, i.e. from October 1995 to September 1998.[8] Figure 2 indicates a rapid fall in the SOI from about March 1997, coinciding with the manifestation of the most recent El Niño event. El Niño conditions persisted until May 1998, followed by a rapid rise in the SOI that was triggered by the demise of El Niño.

Fortunately, the El Niño phenomenon did not have the detrimental impact on South Africa's water resources as predicted. Inspection of Fig. 1 reveals that the dams stood at approximately 90 % full at the onset of El Niño. By the time El Niño had dissipated, the dams were at more or less the same percentage of capacity — a clear indication that El Niño did not have the effect as predicted. It was only after the demise of El Niño that unusually dry conditions prevailed (albeit in the normally dry winter season typified by most of South Africa), resulting in a fairly rapid drop in storage over the period July to September 1998.

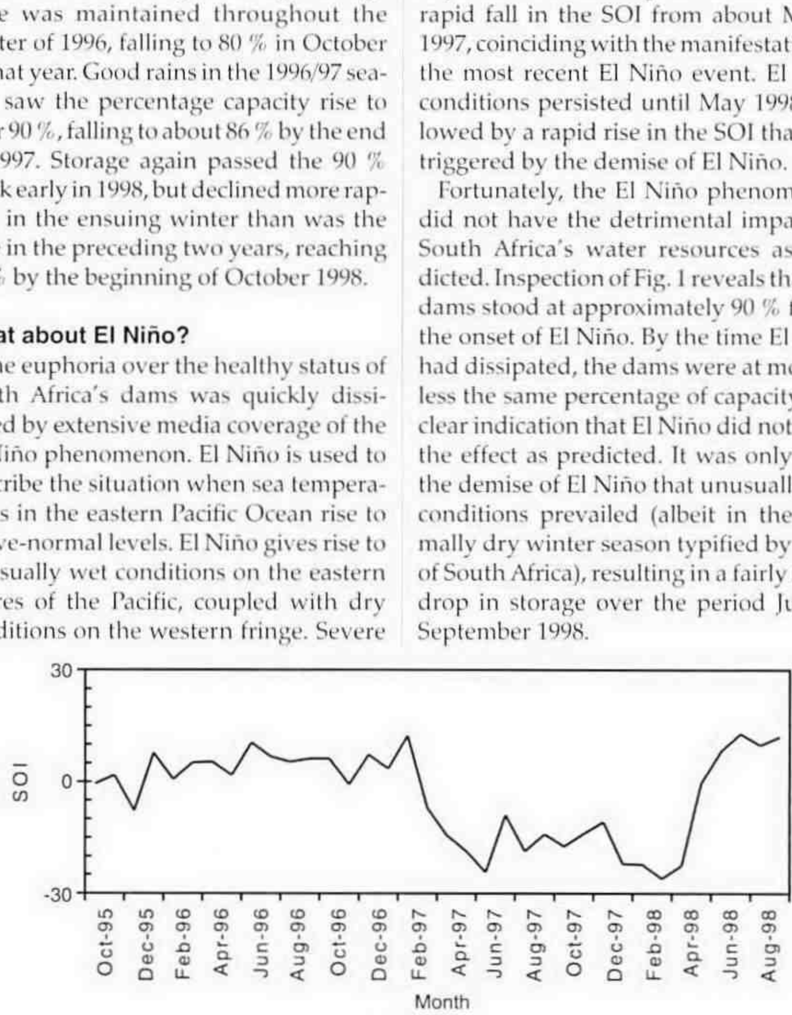

Fig. 2. Southern Oscillation Index (October 1995 to September 1998).

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Concluding remarks

The rapid recovery in the health of South Africa's water resources, which occurred after the severe drought of the early 1990s, has been sustained despite the appearance of El Niño that severely affected weather patterns in the Pacific Rim. Recent research suggests that rainfall conditions over southern Africa are linked to sea-surface temperature (SST) anomalies in the southwest Indian and southeast Atlantic oceans.[9] El Niño should therefore be seen as just one of the SST anomalies affecting rainfall patterns over southern Africa. Accordingly, predictions based solely on El Niño should be treated with caution, as they cannot be expected to give even a reasonably accurate picture of likely weather conditions over the subcontinent.

Unreliable predictions can be extremely counter-productive, since (a) they instill an unwarranted pessimistic attitude and (b) they cause the public to ignore future warnings based on the same shaky ground. For example, many farmers apparently did not plant crops because they were warned that El Niño would almost inevitably bring about crop failures on a large scale. A water-scarce country such as South Africa would benefit enormously from reliable long-range weather forecasts but, until such forecasts become a reality, forecasters should exercise great caution in dealing with the public and the media.

Groundwater

National Water Act

The National Water Act was promulgated in 1998 and has wide-ranging implications for groundwater. The status of groundwater has now been changed from one of a privately owned resource asset, coupled to property, to one of a public, or national, resource asset with shared use entitlements. Groundwater is now considered a strategic resource on account of its role in meeting the large unmet basic water supply needs, especially in rural areas. These changes already start having a major influence on groundwater research and development in the country.

Hydrogeological maps

A two-pronged approach to a hydrogeological mapping programme was begun in the early 1990s with overall objective:

- compilation of *national maps*, and
- compilation of *regional maps*.

National maps

The following national maps have been completed:

- Groundwater Resources of the Republic of South Africa, together with its accompanying brochure.[10]
- Groundwater Harvest Potential of the Republic of South Africa, together with its accompanying brochure.
- Groundwater Vulnerability of the Republic of South Africa.
- Classification of Aquifers in the Republic of South Africa.
- A map depicting groundwater usage is also being compiled.

Regional maps

A mapping programme is in place to complete the series of 23 hydrogeological maps covering the entire country at a scale of 1:500 000 by the year 2000. To date, three of these maps have been completed, namely Queenstown, Port Elizabeth and Durban, together with their accompanying brochures. These maps are proving particularly useful in assisting with water resource planning at the regional and district level, and in fostering a public awareness of the groundwater resources in general in the country.

National Groundwater Information System

The National Groundwater Database, which has been in existence since 1985, has now been overtaken by advances in information technology and is no longer able effectively to meet the requirements of a burgeoning client/user base. Neither is it able to provide the technical support required by the Department of Water Affairs and Forestry in terms of the implementation of the new National Water Act. A conceptual specification has recently been released in which a phased approach has been proposed to establish a new National Groundwater Information System based on modern IT principles. As part of the strategy it is proposed to establish a distributed and integrated groundwater information system in each of the department's regions, each with its own regional groundwater datasets. These datasets will be replicated in a national groundwater archive. A joint venture is about to be entered into with the TNO-NITG in Delft in the Netherlands to make use of their Regional Geo-Information System (REGIS) under licence, after system modification and customization, to cater for southern African hydrogeological conditions. Other off-line users will be catered for where stand-alone computers only are used, and appropriate computer software will be made available. This vision is illustrated in Fig. 3.

The Department of Water Affairs and Forestry has its own website, which is being extensively used to disseminate various groundwater-related data and information in text and map form. A departmental data server is also in operation that caters for the uploading and downloading of salient information from groundwater consultants' reports nationwide.

Groundwater research issues

A number of groundwater research programmes have been identified as part of the Groundwater Master Plan compiled by the Water Research Commission (WRC). These include the following:

- Fractured-rock aquifer research programme.
- Groundwater reserve determination research programme.
- Sustainable groundwater management

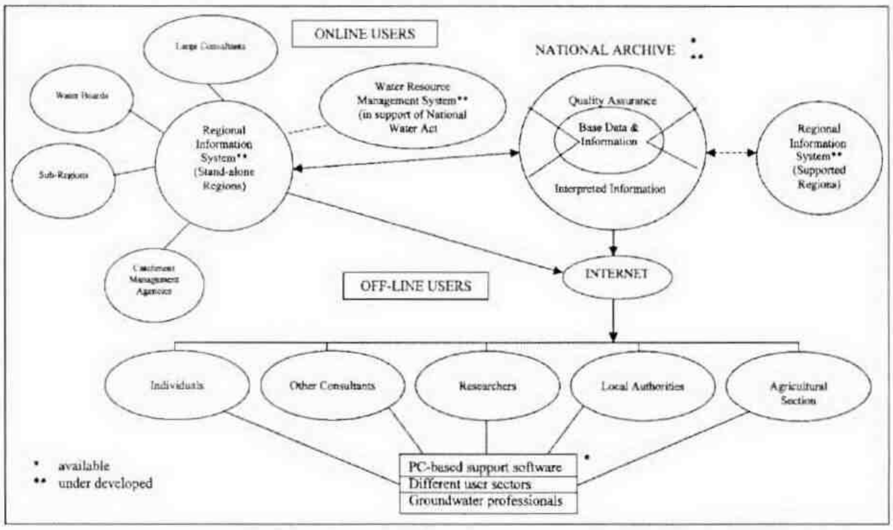

Fig. 3. Vision for a National Groundwater Information System for South Africa.

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and utilization research programme.

- Groundwater research in support of the community water supply and sanitation programme.
- Groundwater quality research programme.

During the first half of 1999, a process will be put in place to review the groundwater issues and research needs for the next five years. This is particularly pertinent in view of changing legislation affecting new priorities and the management arrangements in the water sector.

The WRC Coordinating Committee for Geohydrological Research strategy for attaining prioritized goals include the following:

- Identification and characterization of groundwater resources of South Africa in terms of their occurrence, quality and development potential.
- Determination of the occurrence, degree and potential for groundwater contamination.
- Optimization of groundwater utilization for all communities through an integrated management approach.
- An investigation of groundwater-environmental interactions.
- Development and implementation of suitable tools and techniques that would aid in achieving the goals and objectives set out above.

A number of major advances have been made in the recent past in groundwater studies, namely:

Groundwater recharge estimation

In preparation for improved management of groundwater in South Africa, a comprehensive manual on groundwater recharge estimation has been completed.[11] The manual provides results for a full range of methodologies and most typical groundwater occurrences in South Africa.

Groundwater quality protection

Unique research work is being undertaken to develop groundwater protection zoning for South Africa's predominantly hard-rock aquifers with tracer experiments.[12] At the same time a national ambient groundwater quality monitoring network is being established. It is planned to follow this up with regional networks in support of aquifer management as well as local networks in support of local groundwater abstraction and impact management.[13]

Fractured-rock aquifers

Fractured-rock aquifer research has progressed considerably at micro, meso and macro scale, in particular through the hydraulic behaviour studies at the Campus Test Site, a well-planned assemblage of production, observation and core boreholes at the Institute for Groundwater Studies in Bloemfontein.[14]

Groundwater modelling

South Africa has a strong groundwater modelling capacity at the Institute for Groundwater Studies. Comprehensive and user-friendly modelling packages going under the software names of AQUAMOD and AQUAWIN have been developed. They are compatible with surface water management models and cater for incorporation of uncertainty and risk in the groundwater analyses.[15]

Education and training

A one-year B.Sc. (Honours) level international groundwater course has been offered since 1994 at the Institute for Groundwater Studies of the University of the Orange Free State with sponsorship from the Carl Duisberg Gesellschaft in Germany. It provides an excellent complement to the long-established Honours course in geohydrology at the university and has already started to make a contribution to groundwater practice in a number of African countries and to urgently needed employment equity in South Africa.

The Swedish government through SIDA continues to promote advanced international training in Göteborg. One of the courses, 'Management of Groundwater Supply for Urban Areas', has been followed by a number of South African hydrogeologists over the last four years, and will continue to do so. The course has a proven track record and has been found to be very beneficial to participants, particularly those with little formal training in hydrogeology.

The Groundwater Division affiliated to the Geological Society of South Africa continues to provide short courses in groundwater, including the 'Introduction to Groundwater' three-day course. The International Association of Hydrogeologists is holding its XXXth Congress 2000 in Cape Town with theme *Groundwater: Past Achievements and Future Challenges.*

Much greater focus and coordination of education and training in the water resources field is envisaged through a proposed system of networking of users and education and training providers. The proposal for a Framework Programme of Education and Training in Water (FET-WATER) was made by a UNESCO-sponsored mission to South Africa in 1998.[16]

Water resources systems analysis

Surface runoff is highly erratic throughout most parts of the country and long drought periods, often in excess of 10 years, are characteristic of the variability in runoff. In order to provide reliable water supplies under such conditions, South Africa's water supply infrastructure is integrated and sophisticated, often involving numerous large reservoirs, pipelines, pumps and water-transfer schemes. In some cases, water is transferred more than 1000 km with pumping heads in excess of 500 m. Figure 4 provides an indication of the major transfer schemes throughout the country.

To manage the various water supply and transfer schemes and to use the available resources in an optimal manner, South Africa has developed highly sophisticated analysis techniques often based on stochastically generated streamflow sequences.

Over the last four years (1995–1998), the water resources network models have increased in size and complexity to stimulate the inter-connectivity of the existing system with proposed future developments. In particular, the Vaal River System has expanded to incorporate several new subsystems in adjacent catchments in a quest to provide water to the ever-thirsty central industrial area of the Gauteng region, which can be considered the industrial powerhouse of southern Africa. This was the first major area in South Africa where the demand for water outstripped local supplies, and from a national viewpoint is of major strategic importance for the following reasons:

- Over 80 % of South Africa's electricity is generated there.
- South Africa's two largest petrochemical plants are located there.
- Numerous large mines (gold, platinum and coal) are located in the area.
- Over 50 % of South Africa's population reside in the area.
- Over 50 % of South Africa's GNP is produced in the area.

In view of the importance of the water supply to the Vaal River Supply Area, a series of water resource assessment studies were initiated around 1996 and are collectively referred to as the Vaal Augmentation Planning Studies (VAPS). The VAPS project involved all of the country's major consultants concerned with water-resource assessment and was initiated to identify and evaluate the

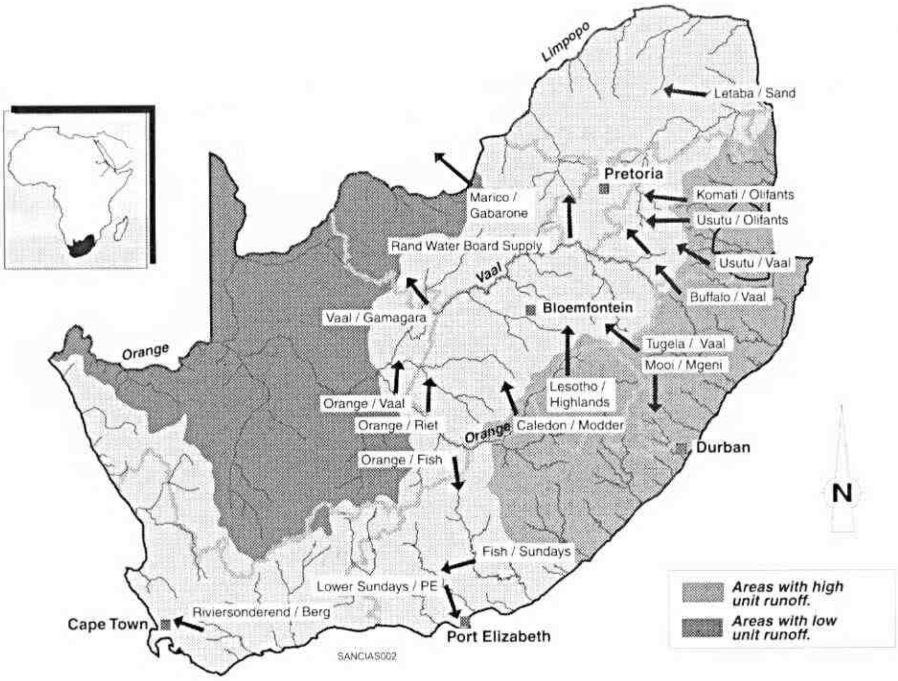

Fig. 4. Major water transfer schemes in South Africa.

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next major interbasin transfer scheme to follow Phase 1 of the large Lesotho Highlands Water Project (LHWP). The VAPS project is clearly one of the most important projects to be undertaken in South Africa during the last 10 years.

Compared to less than 10 years ago, when these analyses could only be undertaken on large mainframe computer systems, it is now possible to run software on personal computers. The tremendous progress in computing power at an affordable price has recently opened up the whole area of water resource analysis and management in South Africa to numerous small companies that could not enter this highly specialized field. This in turn has created the need for training and transfer of technology. Courses on the South African techniques have been presented at universities in South Africa and also in several other countries, including the USA, where the innovative approaches were very well received. It is anticipated that the software will be developed to a stage where it can be distributed and used freely outside South Africa.

Analysis procedure

The components of the analysis procedure used in South Africa can broadly be grouped in standard hydrological assessments, water quality modelling and system analysis as depicted in Fig. 5. As can be seen from this figure, much of the initial approach is based on standard hydrological modelling techniques used throughout the world. The collection and collation of hydrological data as well as the infilling and extension of the streamflow sequences using deterministic rainfall/runoff modelling is common practice in most countries. Where the procedure may differ from other countries, is in the use of stochastically generated streamflow sequences that are provided as input to a highly sophisticated water-resources network model.

The generation of the stochastic streamflow sequences is fully described in a paper[17] and also in a user manual.[18] The stochastic streamflow model also includes a complete suite of detailed checking procedures to ensure that the sequences generated are realistic and have similar characteristics to the historical sequences. This aspect of the stochastic modelling is as important as, if not more important than, the actual streamflow generation.

The system modelling is undertaken using the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM). Both models are based on similar principles involving the network modelling approach first proposed by Sigvaldason.[19]

The basic WRYM is capable of simulating a wide variety of operating policies in a multipurpose multi-reservoir system. It is capable of analysing the yield and reliability characteristics of large integrated systems (up to 200 reservoirs), in which the operating rules and network configuration are contained in system data files and not hard-coded into the model. This makes the model a very flexible and powerful tool for analysing complex water resources systems and it has been used in practice for the last 10 years to operate and manage South Africa's water resources. The model is designed to analyse a water resource system at a fixed point in time with demands and network

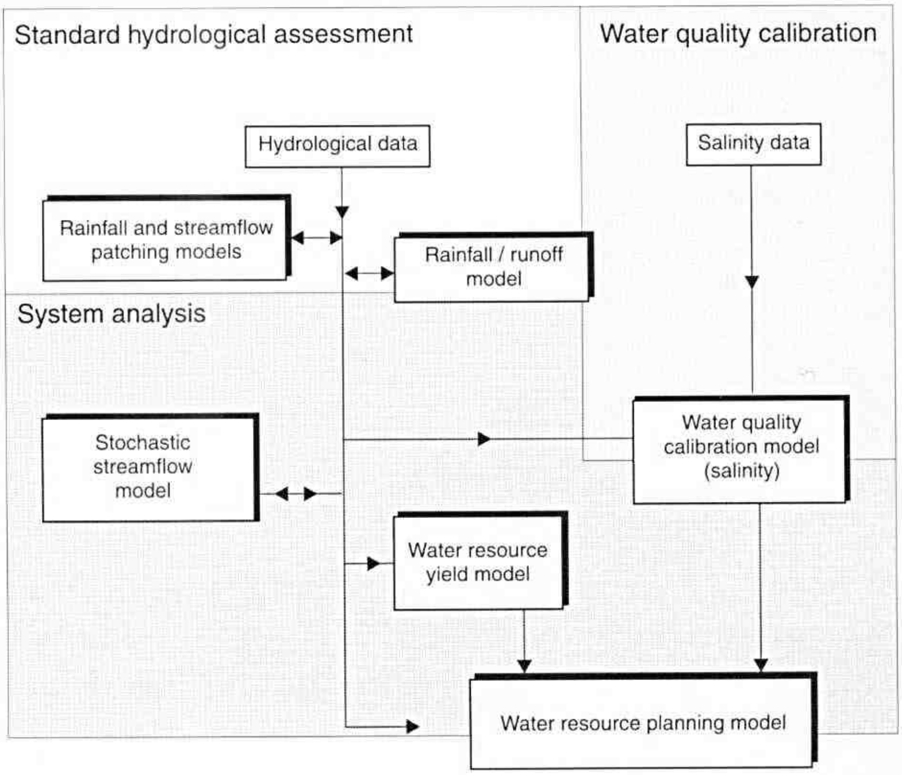

Fig. 5. Analysis procedure.

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limitations that do not change during the simulation period. The analysis is undertaken using a monthly time-step and it usually covers a period of more than 70 years. The model provides estimates of the system yield and associated reliability of yield for user-defined operating rules. In this manner the user can examine and change the operating rules to 'tune' a large system and gain a proper understanding of the various interactions between the different reservoirs, pipelines and transfers etc.

The WRPM is able to handle changing system configurations and demands with time and is used specifically for long-term planning analyses as well as real-time operating. Both models are used together on most projects as some of the yield/reliability results from the WRYM are used as input to the WRPM. An additional key feature of the WRPM is the ability to model water quality (salinity) on the basis of mass balance. Although numerous other models are also available that can model a multitude of both conservative and non-conservative water quality variables, in South Africa the major quality-related operating decisions are addressed using total dissolved solids (TDS) on a monthly time step.

Typical model output

Typical results from the two system models (WRYM and WRPM) include:

- Yield reliability relationships for a particular set of operating rules.
- Influence of different water quality blending options.
- Scheduling of possible future augmentation schemes.
- Influence of water demand management options on the phasing of possible future developments (Fig. 6).
- Assessment of hydropower generation and the investigation of possible conflicts between hydropower demands and consumptive demands (e.g., urban, industrial, irrigation).
- Determination of curtailment strategies for the implementation of water restrictions during periods of drought.
- Influence of new environmental requirements on the system yield.
- Influence of different operating rules on likely future reservoir trajectory (Fig. 7).

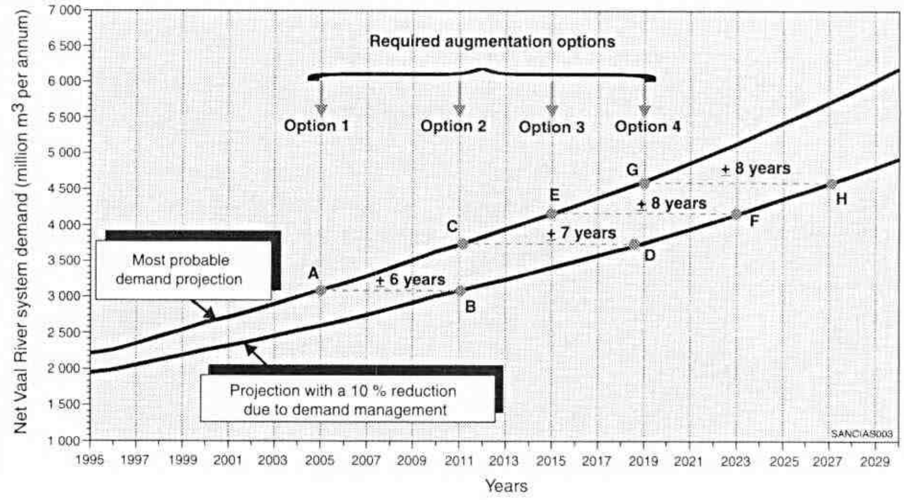
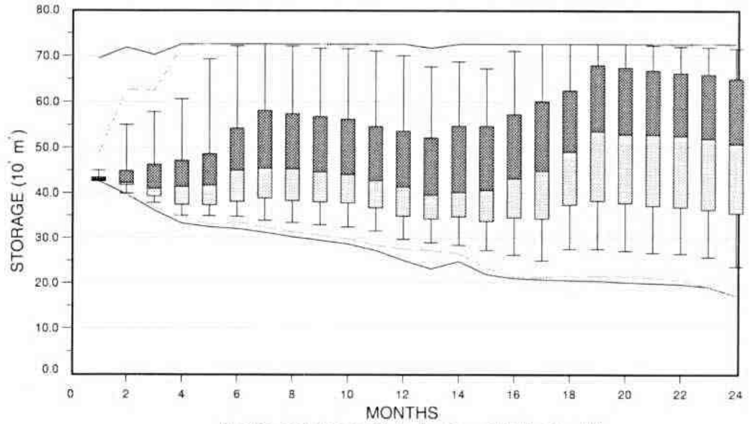


Fig. 6. Influence of water demand management on phasing of future development options (Rademeyer *et al.*[19]).

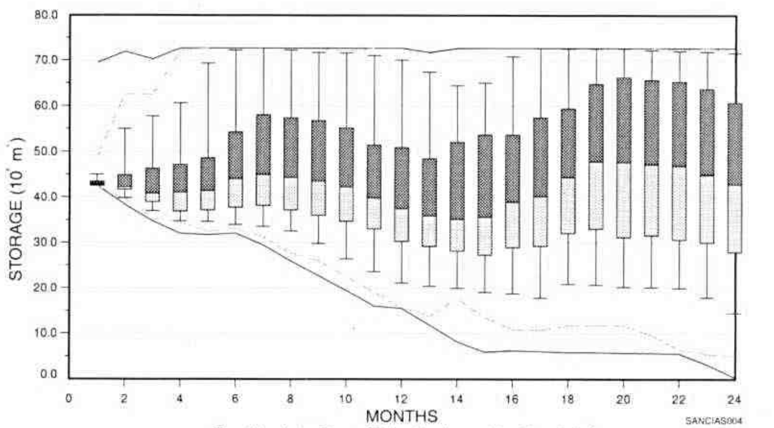
Future perspective on water resources modelling

The current water resources analysis procedures have been tested in South Africa for more than 10 years and will remain the backbone for analysis, planning and water-resources management for many years to come. It is anticipated that the models will have to be modified and upgraded to provide decision support to the Catchment Management Agencies that will soon be formed under the new National Water Act. This will involve converting the models from DOS-based programs to user-friendly Windows-based programs, and require extensive training to equip users with a sound hydrological and modelling background.

Further changes to the models will involve the integration of different software packages into a single model and the facility to model at different time steps down to a daily level, which may incorporate hydrodynamic routing capabilities. In addition to the model development, awareness of the models and the analysis



Rustfontein Dam (Priority from Welbedacht)



Rustfontein Dam (Priority from Rustfontein)

Fig. 7. Example showing use of Water Resources Yield Model in assessing reservoir trajectories for different operating rules.

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techniques will be promoted outside South Africa to other countries where similar water resource problems are encountered. This will be particularly relevant to countries in southern Africa, where shared water resources require a standard analysis approach to manage the available resources in an efficient and transparent manner.

Water quality

The availability and quality of freshwater supplies have long been recognized by water-resource managers as being inextricably linked and having an important potential to limit and possibly even halt development within South Africa. Our appreciation of the importance of water quality issues has been heightened by the dramatic effects of recent droughts, when many of the smaller perennial rivers ceased to flow and water quality deteriorated dramatically owing to continued discharges of treated domestic and industrial effluents. Further emphasis has been provided by the implications inherent in the need to ensure safe supplies of drinking water to the many communities and individuals who previously have had to rely on uncertain surface water supplies which were often of dubious quality.

The development of a National Water Policy for South Africa, followed by the promulgation of the new Water Act, signalled important new milestones in the history of South African water-resource management. Both of these landmark events emphasized the need to ensure that water quality issues remain an integral part of all water resource management plans and actions. While the primary focus of attention was quite properly placed on meeting the basic human needs of all water users, much greater emphasis was also placed on meeting the water quantity and quality requirements of aquatic ecosystems. This latter emphasis arose out of the clear realization that the surface water resources of the country will be unable to sustain the demands that continue to be made on them unless aquatic ecosystems are properly managed on a sustainable basis. This new focus of attention has placed a heavy responsibility on the Department of Water Affairs and Forestry, as custodian of the country's water resources.

A review of the past few years

The adverse effects of recent droughts, plus the need to develop appropriate new policies and strategies for water resource management, have also led to important changes in the policies and technical approaches adopted by water resource managers. A central component of this change has been the shift in emphasis from development of new water resources to a drive to improve the management of available resources. In this process, water quality and water quantity aspects have continued to be considered together.

Before the promulgation of the new Water Act in 1998, perhaps the most important and far-reaching developments in the field of water quality centred on the appearance of revised water-quality guidelines for domestic, industrial, agricultural and recreational uses of water.[20] However, while these documents provided water resource managers with key insights into the water quality demands of these user sectors, it was the simultaneous appearance of the first version of water quality guidelines for aquatic ecosystems that signalled an important shift in policy. This change, namely acceptance that aquatic ecosystems were not merely 'users' of water but that they also comprised components of the resource itself, has helped water resource managers to create a much greater awareness of the importance of maintaining aquatic ecosystem health. This trend has also been reflected in a wider acceptance of biological monitoring as a water quality management tool for rivers and impoundments. Notwithstanding the many technical difficulties that must still be overcome before the potential benefits of biological monitoring are fully realized, widespread acceptance of this approach has helped to ensure that aquatic ecosystems receive appropriate recognition from all water user sectors.

The new National Water Policy outlined a broad approach to the protection of the country's water resources, including protection of surface waters, groundwater, wetlands and estuaries. This resource protection approach outlined four key features within a structured decision-making framework,[21] namely:

- *Resource-directed measures,* which focus on each water resource as an ecosystem and set clear objectives (resource quality objectives) for attaining the desired level of protection for each resource.
- *Source-directed measures,* which include a wide range of regulatory measures (including waste-water standards and water-use licences) intended to control the sources of adverse impacts on water resources.
- *Demand management measures,* which are intended to ensure that water utilization patterns are driven by considerations of efficiency of use and remain within the limits required for protection of the resource.
- *Monitoring and auditing measures,* which will reflect the status of the country's water resources and determine whether or not quality objectives that have been set for specific water resources are indeed being met by the respective water-resource managers.

The Department of Water Affairs and Forestry has the primary responsibility for development of appropriate techniques, which will ensure the implementation of these approaches.

Within the arena of water resource protection, a central theme has been the recognition of a so-called 'Reserve'. The 'Reserve' embodies the concept that, as far as possible, sufficient water of suitable quality must be available to meet the basic human needs of all water users and the aquatic ecosystem, before water can be allocated to off-channel users. The Reserve concept therefore marks a dramatic shift in emphasis from earlier water resource allocation principles where water from a river could almost invariably be allocated to off-channel water users without explicit concern for the maintenance of aquatic ecosystems or to provision of water supplies for downstream riparian users.

While it is relatively simple in concept to embody a Reserve to meet basic human needs and aquatic ecosystem functioning in all water resource management plans, the process is less straightforward in practice.[22] This problem has arisen primarily because of the almost complete absence of accepted techniques with which to calculate the actual quantities and qualities of water that are needed by aquatic ecosystems during an annual cycle and under different conditions of flood and drought. As a result, considerable attention has now been focused on the development of a suite of suitable techniques, which will allow aquatic scientists and water-resource managers to determine the Reserve with a high degree of confidence.[23]

In terms of the new Water Act, all licences or permits that are granted for the discharge of effluent into a surface water resource or for the abstraction of water from surface and groundwater resources must take due consideration of the Reserve. Therefore, the need to develop acceptable techniques for calculating the quantity and quality components of the Reserve is becoming increasingly urgent. Given the immediate and short-term needs, water resource managers will have to rely on robust 'estimation' techniques that incorporate precautionary principles, while further investigations continue in the medium-term to develop more accurate and scientifically-sound techniques.

Concluding remarks

The rising population and accompanying gradual improvements in quality of life will fuel demands for water of appropriate quality. This trend will continue to escalate as we enter the new millennium, placing ever greater demands on our dwindling water resources. While the primary responsibility for effective and efficient water-resource management will remain with the Department of Water Affairs and Forestry, a concerted effort will be required from every person in the country if we are to achieve the national goal of sustainable use of our scarce water resources.

Sediment transport and deposition

While reservoir sedimentation and other sediment-related problems are becoming more and more prevalent around the globe, such problems have long become serious in southern Africa. With the limited runoff from most local catchments, dams have had to be built to store the runoff from large catchments. Such large catchments tend to produce large sediment loads. As these sediment loads are trapped within reservoirs, storage space becomes depleted rapidly. At the same time, trapping of sediments within the reservoirs and storage of water cause changes in flow patterns as well as sediment loads downstream of reservoirs, leading to geomorphological changes over considerable distances downstream. At the other end of the scale, the movement and deposition of highly valuable gold and other heavy minerals have been studied with the aim of finding ancient deposits.

Different stimuli have therefore led to extensive research into different aspects of sediment transport during recent years. These aspects have included:

(i) Investigations into sediment yields from catchments and resulting sediment loads in rivers, culminating in the development of a new sediment yield map of southern Africa.
(ii) Ways and means of dealing with reservoir sedimentation have been researched on an extensive scale.
(iii) Changes in river geomorphology, particularly in ecologically sensitive areas.
(iv) Development of new flow measurement structures that can be used to measure river discharges accurately in sediment-laden rivers.
(v) Transport and deposition of heavy mineral particles.

The sediment yield map of southern Africa

The most recent sediment yield map of southern Africa[24] (Fig. 8) was prepared for a wide range of applications. Whereas previous maps had served primarily to predict sediment loads that would enter planned reservoirs, the most recent map includes confidence bands that indicate the likelihood of a given yield value being exceeded.

Dealing with reservoir sedimentation

In a comprehensive study, ways and means were investigated for overcoming the problems associated with reservoir sedimentation.[25] Guidelines were prepared on appropriate measures for limiting sediment build-up. A condensed version of the abovementioned report is being printed as the official guidelines of the International Commission on Large Dams.

River geomorphology

Different aspects of river geomorphology have been studied, with the emphasis on the rivers in the Kruger National Park. The following aspects were investigated: channel resistance,[26,27] channel deformation,[28,29] river classification and management.[27,29]

Flow measurement

A new type of structure[30] has been developed for flow measurement in sediment-laden rivers. This structure serves to limit sediment build-up in areas where sediment deposition could affect the accuracy of measurement.

Deposition of heavy metals

With the significance of the mining industry in South Africa, it is not surprising that transport and deposition problems of heavy metals[31,32] as well as diamonds have been studied in detail.

Remote sensing

The use of remote sensing in hydrology and water management received a boost since 1995 with the development of the National Land Cover (NLC) database.[33] The project is a joint venture between the Division of Water, Environment and Forestry Technology of the CSIR, the Agricultural Research Council with financial support from the departments of Agriculture, Environment Affairs and Tourism, Water Affairs and Forestry and the SA National Defence Force.

The entire country will be covered with 1:250 000 maps, including Swaziland and Lesotho. The first data became commercially available in 1997 and each dataset will be released into the public domain after 24 months. The classification scheme has been designed to conform (as far as possible) to internationally accepted classification standards and conventions, in order to ensure cross-border compatibility such as those already in use in the Zimbabwe, VegRIS and the proposed FAO's Africover project.

The NLC project incorporated four basic stages in the compilation of the digital land-cover database:

- Pre-annotation field orientation.
- Image annotation and land-cover mapping.
- Digitization of annotated land-cover data.
- Field verification and data validation.

The basic data were transformed into 1:250 000 scale Landsat™ Space Maps after which manual photo-interpretation techniques were used. Skilled photo-interpreters with extensive local knowledge are able to utilize feature shape, location, texture, context as well as spectral characteristics when classifying land-cover. This resulted also in a considerable overall saving in project costs compared with full scale digital image processing.

Approximately 180 sample sites were assessed within each Space Map, of which 50 % where evaluated in the field and the rest using aerial photography.

Geographical data accuracy was ensured using between 15 and 30 ground control points.

The selection criteria for TM data was as follows:

- Only imagery after 1 January 1993.
- Preference to the most recent imagery if alternatives are available .
- As far as possible a standardized seasonal time frame would be adopted.

Two criteria were used, firstly *optimum season* (i.e., uniform vegetation growth stage) which was taken to be April, May and June in the summer rainfall areas and September to December in the winter rainfall areas. Secondly, *seasonal rainfall* (uniform vegetation response and condition, based on the analysis of decile rainfall data for three month period prior to the beginning of each optimum season). *Optimum seasons* were defined on the following parameters:

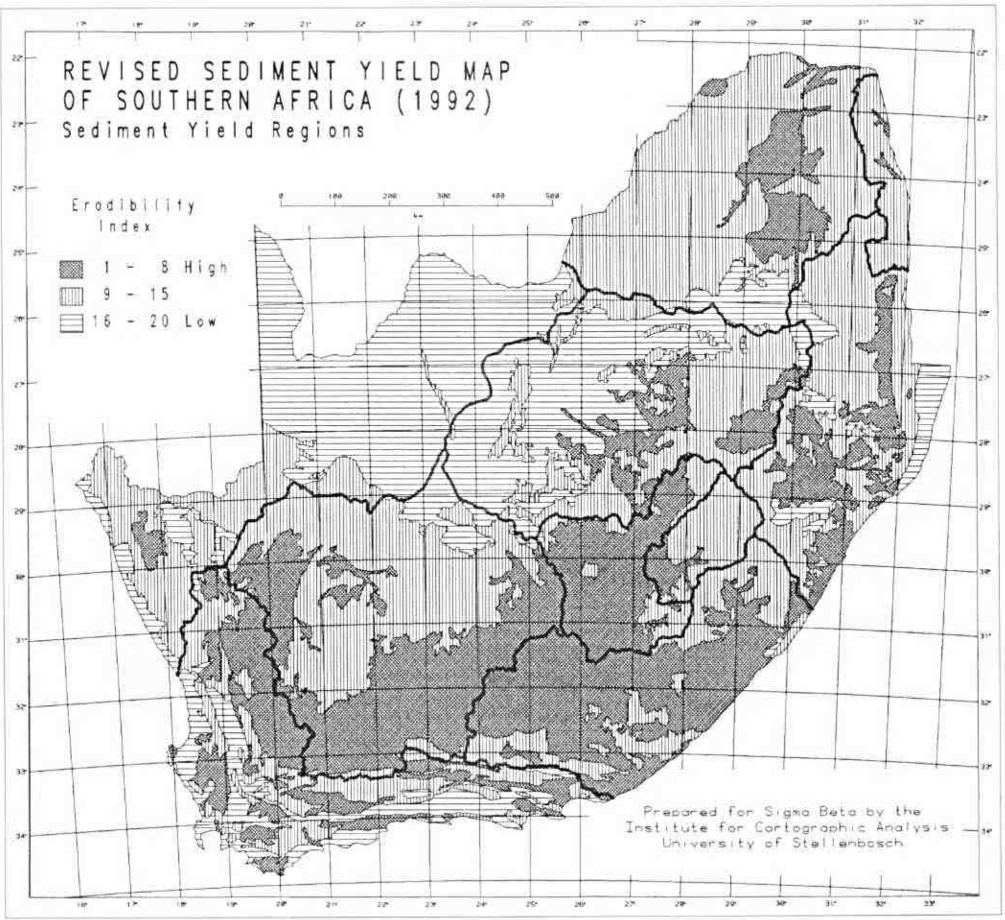

Fig. 8. Sediment yield map of southern Africa (1992).

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- Minimum cloud cover.
- Minimum terrain shadowing.
- Minimum snow cover (Lesotho and Cape mountains).
- Minimum fire scar effects.
- Maximum spectral difference between cultivated and natural vegetation.
- Maximum spectral difference between grassland and tree/bush cover.

The external auditor of the project, M.J. Clark, stated:[34]

> The NIC database is now in its final phase of construction and represents a major national planning, management and scientific resource in its own right but its value would be hugely enhanced by the implementation of an on-going monitoring system to permit assessment of land-cover change.

Work will now start in using the data in hydrological models and the management of 'Stream flow reduction activities' provided for in the new Water Act.

More detail on remote-sensing products and activities can continuously be obtained from the Satellite Applications Centre's website: http://www.sac.co.za

Atmosphere-soil-vegetation interaction

A small, but very active research community in South Africa, with major centres of expertise at the universities of Natal and Pretoria as well as the CSIR, is involved in research activities in this IAHS Commission. Their work has received new impetus by the revised National Water Act of 1998, placing considerable emphasis on land-use and land-management influences on hydrological responses, because many of the research findings will eventually be incorporated into hydrological simulation models that will be used, for example, in regulatory decision-making and arbitration.

The CSIR's process hydrologists have been researching water-use efficiencies of commercially grown plantation trees, with major investigations into correlations of transpiration *vs* trunk growth using heat pulse velocity methods, as well as studying evaporation rates from different tree species, sugarcane and grassland under various hydroclimatic regimes using Bowen ratio techniques, including water use : biomass relations for food and fodder crops.

Field experimental work carried out by the University of Natal's Department of Agricultural Engineering revolves around hillslope hydrological process and dynamics studies in an intensively instrumented research catchment in the northeastern Cape, in which the present natural grassland land cover will be replaced by exotic tree species after a further year's investigation under 'pristine' conditions.[35]

Allied with the hillslope hydrology has been the initial development and testing of the raster-based TopACRU model, a modification and improvement on the widely used Topmodel, with the aim of determining and modelling source areas of sediment yield.

Both the University of Natal and CSIR are conducting field experiments on riparian water use under different planted land uses, invasive trees and indigenous riparian plant communities under a range of climate conditions.[36] Riparian water use by alien/exotic vegetation is currently of particular interest in the light of their potential reduction of streamflows in South Africa's generally semiarid conditions, and government has launched a major initiative to clear such riparian growth to enhance streamflows.

In a cooperative project between the universities of Pretoria and Natal, impacts of irrigation with gypsiferous water is being researched on rehabilitated soils from opencast coal mines to assess crop sustainability, the accumulation of gypsum in soil profiles and irrigation rates of contaminants.

Many of the results from the above research eventually find their way into agrohydrological models, particularly the now frequently applied *ACRU* model, a multi-level and multi-purpose physical-conceptual daily and intra-daily time step simulator.[37] *ACRU* is constantly being refined and enhanced (most recently in terms of CO_2 feedback and dynamic vegetation changes in regard to degradation and rehabilitation of grasslands and savanna vegetation) and with its facilities to simulate stormflows, baseflows, sediment yield, irrigation demand/supply, crop yields as well as reservoirs and wetlands in distributed mode, it is being used frequently now in conflict resolutions involving land use impacts and in arbitration.

A milestone in applied research on soil, vegetation and atmospheric interactions was the publication in 1997 of the 'South African Atlas of Agrohydrology and Climatology'.[38] This 276-page atlas contains over 140 high-resolution colour maps covering the physiography and climate of South Africa, as well as crops and water resources aspects.

While the number of scientists engaged in basic and applied hydrologically related process research is small, the research output has generally been of exceptional quality and is highly regarded internationally. Two features bear highlighting in conclusion; one being that scientists are now, more than ever before, collaborating both among disciplines and between institutions. The other is that South Africa is indeed fortunate to have the Water Research Commission, an independent parastatal agency, generously supporting relevant hydrological science through research funding and research coordination.

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