E21675a

Management of Large Water Resource Systems

R S Mckenzie **P G van Rooyen**

ABSTRACT

South Africa has one of the most complicated and integrated water resource systems in the world involving numerous interlinked river systems and major interbasin transfer schemes. The management of the various schemes has become a key issue over the past 15 years resulting in the development of sophisticated systems models which are now used to analyse and operate all of the country's major schemes. The models have been developed through a partnership between the Department of Water Affairs and Forestry in association with several of the country's consultants specialising in this area of expertise. The models have now reached a stage where they are considered to be both practical and sufficiently robust to use in other parts of the world.

Australia and South Africa are quite similar in many respects with regards to the water resources and climate. Both countries share the same problem of large arid or semi-arid areas together with areas where the local water resources are insufficient to meet the existing or predicted future demands. Environmental considerations are also of major importance in both countries which in turn necessitates the effective use of the available resources before any new resources can be developed.

In order to use the available water effectively much effort has been placed on various aspects of Water Demand Management in order to reduce leakage and excessive consumer use. It is also necessary, however, to ensure that the raw water resources are managed in an efficient and practical manner – something that is often easier said than done.

This paper provides general details of the system analysis techniques that have been pioneered in South Africa and discusses the most recent developments that can be used to assist water resource managers in the analysis and planning of their water resource systems.

OVERVIEW OF WATER RESOURCES IN SOUTH AFRICA

South Africa is very similar to Australia in many respects with regards to climate and mineral reserves. While it has vast reserves of many strategic minerals, it is relatively poor with regard to its water resources due mainly to the relatively low rainfall of 497mm which is well below the world average of 860mm/a. In addition, the potential evaporation is in order of 1500mm/a which is relatively high and results in only 8.5% runoff. The combined natural runoff from all of South Africa's rivers is estimated to be in the order of 53 500 million m^3/a details of which are given in **Table 1**.

Although some of the figures given in **Table 1** have since been updated or revised, they provide a realistic summary of the overall water resources for the country. To place these resources in perspective, the total runoff of 53 500 million m^3/a can be expressed as a depth (unit runoff) over the whole country of approximately 42mm/a which is very similar to the corresponding unit runoff for Australia. This is very low compared to most countries and to the world average of 330 mm/a as can be seen in **Table 2** which provides some comparative estimates from around the world.

Not only is the runoff in South Africa very low but it is also highly variable from year to year and from point to point with drought periods in excess of 10 years commonly experienced in many parts of the country. The relatively low runoff coupled to the high variability presents major challenges to South Africa's water supply engineers.

Table 1 : Natural runoff's for major river systems in South Africa

River System	Natural runoff (million m^3/annum)
Breede	2 000
Great Kei	1 100
Komati	3 500
Limpopo	2 300
Northern Natal	5 900
Olifants	3 200
Olifants (Cape)	1 000
Orange (excluding Vaal)	7 600
Southern Cape	3 900
Southern Natal	3 200
Transkei	8 500
Tugela	4 600
Vaal	4 500
Western Cape	2 200
Total	**53 500**

Table 2: Comparison of runoff from various continents and countries

Continent/country	Surface area (million	Runoff (million m^3/a)	Runoff (mm/a)
Africa	30.1	4 184 000	139
Asia	43.5	10 485 000	241
Europa	10.5	2 321 000	221
North America	24.2	6 945 000	286
South America	17.8	10 377 000	582
Brazil	8.5	5 190 000	610
South Africa	1.2	53 500	44
Australia	8.9	343 000	39
USA	9.4	2 478 000	263
World	**134.8**	**44 500 00**	**330**

To overcome the long drought periods and provide a reliable water supply to the country's 40 million inhabitants, many large dams have been constructed to store the water together with ambitious transfer schemes to convey the water from the source basins to the major demand centres. An additional problem faced in South Africa is the fact that the largest water demand centre; that of the Vaal River System (total system demand of approximately 3 000 million m^3/a), is located on the interior plateau some 600 km from the Indian Ocean. This causes major water supply problems which have effectively necessitated the development of a complex water supply infrastructure which must rank as one of the most sophisticated in the world due to the level of integration between the various river basins and transfer schemes. The major water transfer schemes in South Africa are shown in **Figure 1** and some details of the dams and associated transfer schemes are provided in **Table 3**.

DEVELOPMENT OF WATER RESOURCE MODELLING TOOLS IN SOUTH AFRICA

The Vaal River System Supply Area is shown in **Figure 2** and incorporates the whole of the Gauteng region which is effectively the industrial powerhouse of southern Africa. This area was one of the first areas in South Africa to experience problems with meeting the water demands from local resources and is strategically important from a national viewpoint for the following reasons:

- over 80% of SA's electricity is generated in the area (capacity of ± 36 000 MW);
- SA's two largest petro-chemical plants are located in the area;
- numerous large mines(gold, platinum and coal) are located in the area;
- over 50% of SA's population reside in the area;
- over 50% of SA's GNP is produced in the area.

Table 3: Some details of South African Dams and Transfer Schemes

Dams					
Name	**Type**	**Height (m)**	**Reservoir Capacity (million m^3)**	**Reservoir Surface Area (km^2)**	**Comments**
Vaal	Composite Concrete Gravity and Earth Embankment	± 64	2 536	323	Urban demands
Gariep	Double curvature concrete arch	± 88	5 958	374	Irrigation and hydropower
Vanderkloof	Double curvature concrete arch.	± 107	3 255	133	Irrigation and hydropower
Sterkfontein	Earthfill	± 93	2 656	69	Support to Vaal System
Katse	Concrete Arch	± 185	1950	36	Support to Vaal System
Mohale	Rockfill	± 135	938	22	Support to Vaal System
Pongolapoort	Concrete arch	± 89	2 500	-	Irrigation/regulation
Bloemhof	Composite Concrete Gravity and Earth Embankment	± 35	1 270	223	Irrigation
Wolwedans	Arch/Gravity RCC	± 70	24	1	First of its type in world
Inanda	Concrete gravity and earthfill	55	242	14	Urban demands
Selected Transfer Schemes					
Name	**Type**	**size**	**Length**	**Capacity**	**Comments**
Lesotho to South Africa	Concrete lined Tunnel	± 4.5 m dia.	± 82 km	± 30 m^3/s	Gravity tunnels
Orange /Fish Tunnel	Concrete lined tunnel	± 5.35 m dia.	± 83 km	± 54 m^3/s	Longest of its type when constructed in 1975
Tugela/Vaal Transfer scheme	Pumped storage scheme with concrete lined tunnels	-	-	± 218 m^3/s	with annual transfer of ± 630 million m^3 through head of ± 570 m
Komati to Olifants Transfer scheme	Pipelines	-	-	± 9.2 m^3/s	annual transfer of ± 100 million m^3 through head of ± 700 m
Usutu to Olifants transfer scheme	Pipelines and tunnels	-	-	± 2.5 m^3/s	annual transfer of ± 80 million m^3 through 450 m
Assegi to Vaal transfer scheme	Pipelines and tunnels	-	-	± 5.0 m^3/s	annual transfer of ± 90 million m^3 through 377 m
Vaal to Olifants transfer schemes	Mainly pipelines	-	-	-	annual transfer of ± 560 million m^3 .

In 1983 a major water resources evaluation of the Vaal River System was undertaken by the Department of Water Affairs and Forestry (DWAF). In view of the numerous demand centres and complexity of the inter-basin transfers, DWAF identified the need for a systematic and pragmatic approach to the management of the water resources which was not available within South Africa (Basson, et.al, 1994). After considering many water resource models from various parts of the world it was concluded that the most appropriate route to follow was the adoption of the Canadian Acres Reservoir Simulation Program (ARSP) which was the property of ACRES International. The ARSP was considered to be the best model of its type available and a suitable starting point for the development of a new South African model. The ARSP Model was developed over a period of approximately 8 years (1977 to 1984) and the basic philosophy is clearly documented in a paper by Sigvaldeson (1979) while details of the model are provided in the various user guides by Allan (1986). Most of the key technical features of the model are explained in the paper or user guide and the only key component which is not explained in detail is the network solving algorithm used in the model. The solver used in the ARSP Model was a hybrid version of the "Out-of-Kilter" solver and remains proprietary software owned by ACRES. In view of the clear and methodical approach developed by Sigvaldeson and Allen, the same approach can be used with any standard network solver to yield identical results. Full details of how the "out-of-kilter" solver operates are given by Jensen and Barnes (1980).

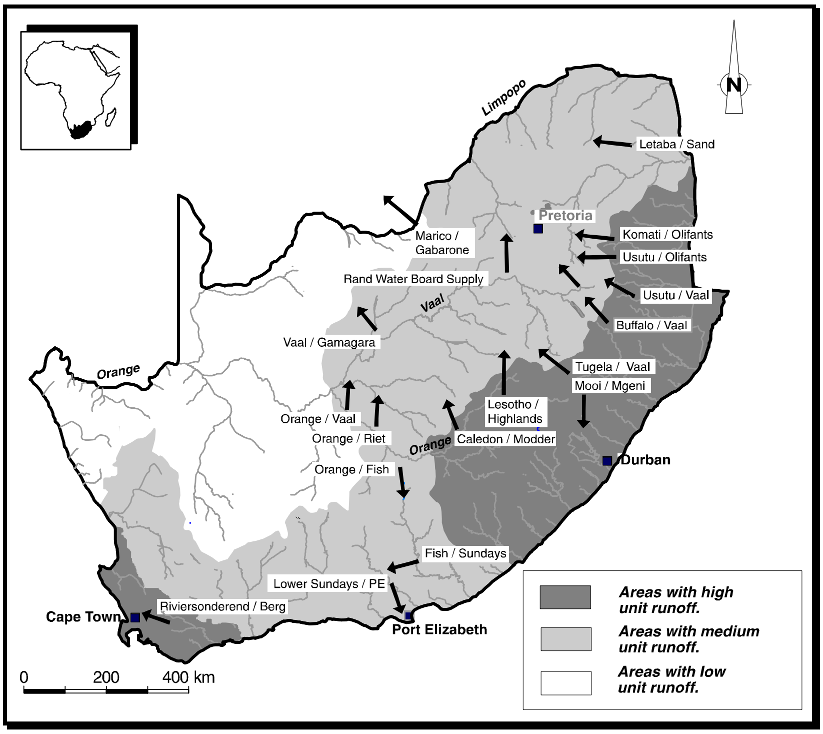

Figure 1: Major inter-basin transfer schemes in South Africa

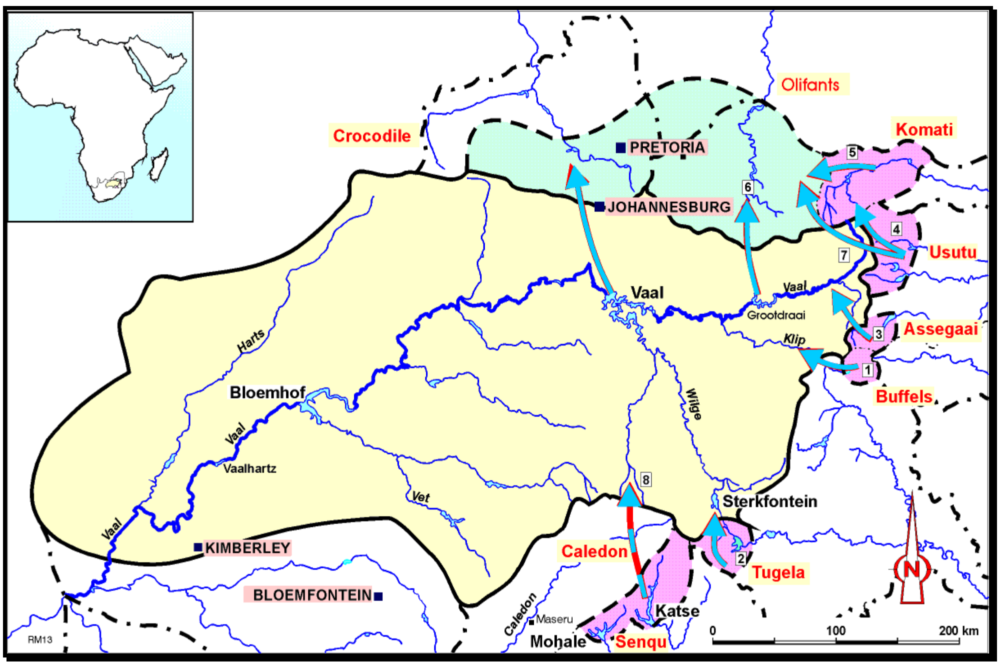

Figure 2: Map of the Vaal River System Supply Area

GENERAL DESCRIPTION OF THE WATER RESOURCES YIELD MODEL (WRYM)

The original ARSP model was not completely suitable for use in South Africa due to the complexity of the water resource networks in the country and the extreme climatic conditions which necessitated the use of stochastically generated streamflow sequences to derive realistic system yields and their associated reliabilities. It was selected by the DWAF, however, due to the fact that it had a very flexible structure which lent itself to further upgrading and modification. The most important aspect of the model was the ability to define a water resource network and the associated operating rules through a set of basic data files. The general structure of the model is shown in **Figure 3** (from Mckenzie and van Rooyen, 1998)

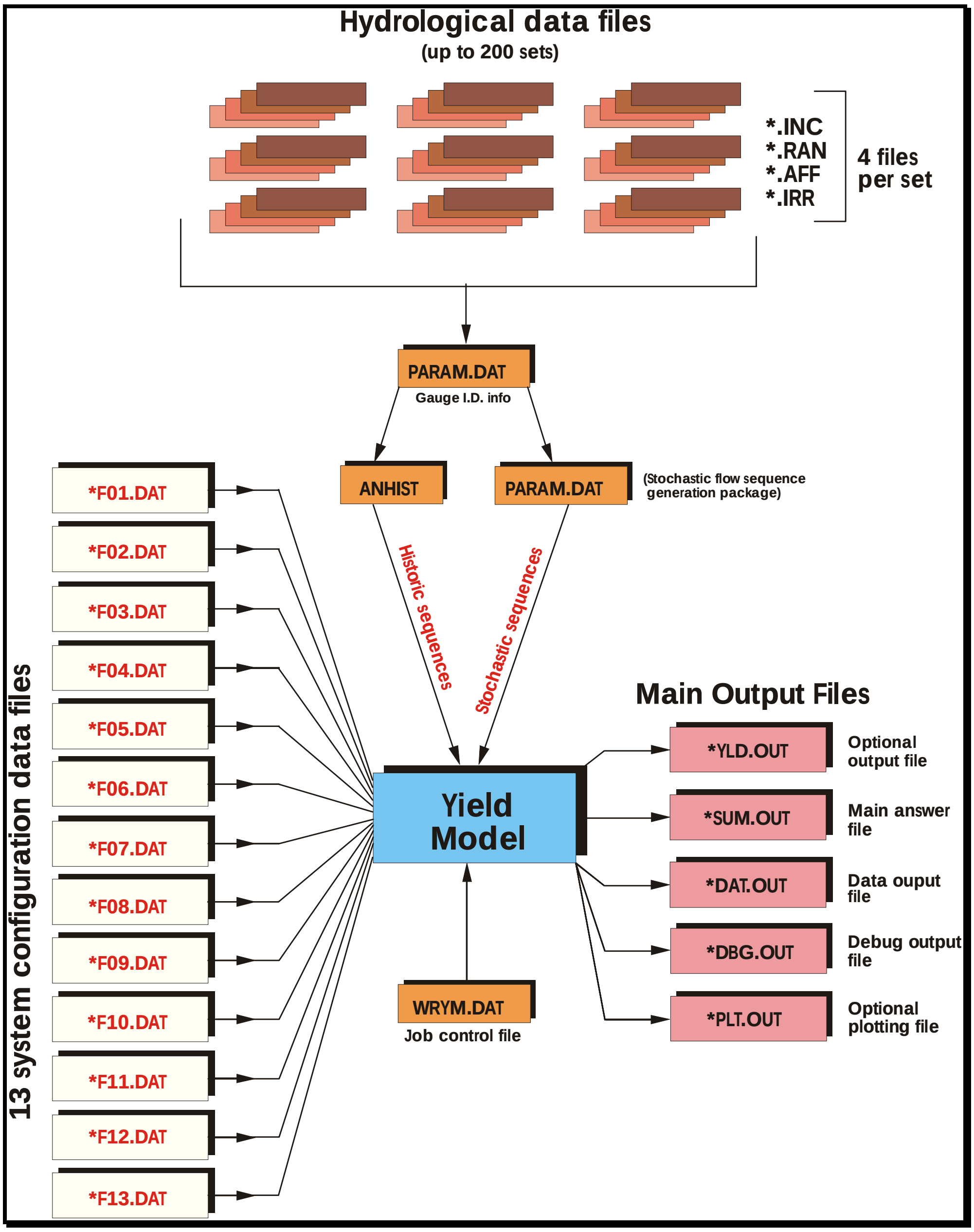

Figure 3: Basic structure of the Water Resources Yield Model

The model operates on a monthly time step and is generally used to analyse a period in the order of 50 to 100 years. It operates by using up to 200 sets of hydrology files. Each set can include up to four separate files including the naturalised streamflow data, the point rainfall data, two diffuse demand files (normally used for irrigation and afforestation). The water resource system and the associated operating rules are defined through a set of 13 data files and in this manner both the network and the operating rules can be changed with ease and without the need to change the source code of the model. The model processes the hydrology which can be either the historical streamflow sequences or up to 1000 sets of stochastically generated streamflow sequences to produce the various answer files. Considerable flexibility exists within the model to adjust the level of detail of the analysis and condense the answer files if desired.

It is important to note that the hydrology files used in the analysis must first be naturalised to correct the flows for any influences of man-made catchment developments. Such influences may be due to irrigation and afforestation or through water abstractions and/or transfers from one catchment to another. In many catchments, such influences are very small while in others they can be significant. If the flows are not naturalised before they are used in the system models, the resulting stochastically generated flows will be flawed as will the yield results. Some details of the significance of naturalising the streamflows are provided in the paper by Mckenzie and Van Vuuren, (1989).

The structure shown in **Figure 3** incorporates several key enhancements to the original ARSP model. Of greatest significance was the development of a robust methodology to simulate and analyse stochastically generated streamflow sequences. This enhancement was required to cope with the long drought periods experienced in South Africa coupled to the relatively short streamflow records (often around 30 to 50 years). Through the use of stochastically generated streamflow sequences, the water resource managers in South Africa are now able to manage the systems with greater confidence and clarity. This effectively added a new dimension to water resource modelling and enabled DWAF to analyse and simulate some of the world's largest and most complex water resource systems in a standard and pragmatic manner. Many other changes and enhancements have been made to the model over the past 18 years to the extent that the current model now bears little similarity to the original structure on which it was based.

WATER RESOURCES PLANNING MODEL (WRPM)

Having developed the WRYM, it became clear that there was a need for a model that can be used to assist with decisions concerning future development options. The WRYM had limited capabilities with regards to future development options and was used to analyse a static system configuration with static system demands and operating rules. To overcome these limitations, a more sophisticated version of the WRYM was developed which could handle changing system configuration with time, changing water demands, changing operating rules as well as modelling certain water quality variables (TDS, Sulphate etc). This new model is currently used together with the yield model on which it is based since both models have their place in the overall water resource management of the country's water resources.

The WRPM is used extensively to analyse and schedule new augmentation schemes as well as to carry out short-term operating analyses which are undertaken annually for most major systems in the country. Through the use of the short-term operating analyses, the water resource managers can detect potential water supply problems at an early stage and appropriate action can be taken to ensure that the water consumers do not experience severe restrictions. In effect, the water resource managers use the models to detect the presence of a drought event and take action in the form of limited water restrictions early on in the drought cycle as opposed to running the system at or near full capacity until the situation becomes so grave that major water restrictions are implemented which in turn damage the economy. Further details of the WRPM can be found in various publications and papers including van Rooyen et. al.(1993 and 2000).

Since the models were first introduced in 1985, there have been very few cases where serious water restrictions have been implemented in South Africa which bears testament to the success and value of the models and associated analysis techniques.

LATEST DEVELOPMENTS IN WATER RESOURCE MODELLING IN SA

Since system modelling was first introduced into South Africa in 1985, major changes have taken place with the result that the models are continually being improved and modified. The original models were based on a VAX Mainframe and written in standard FORTRAN. As technology developed, the models were modified to run firstly on personal computers under the UNIX operating system and later on the DOS operating system. During this time, the basic coded remained virtually unaltered since only the standard FORTRAN functions were used in the models and no VAX or UNIX specific functions were implemented. With the introduction of the Windows operating system, the models were modified to operate under the Windows system.

In the past few years it has become evident that there are tremendous advantages to be gained from using the Windows operating system and in particular the associated graphics capabilities. The models were developed from a non-graphical background with the result that the graphical features of the models and the "user-friendliness" of the models were neglected to a large degree. Various pre and post processors were written in different computer languages including C, Visual Basic, Delphi and several others. After careful consideration it has been concluded that Delphi will be adopted as the basic platform for all future development. In this regard, the latest prototype of the WRYM has already been incorporated into a Delphi Graphical User Interface. Many of the basic calculations are still undertaken in FORTRAN, however, these are slowly being replaced by Delphi routines as further development takes place.

A simplified version of the WRYM is now available as a Windows package (SAWRAM) in which the user is unaware of any Fortran based code since all interaction between the user and the model takes place through a Delphi interface. Similarly, the original self contained version of the Stochastic Model, GENMAC (Mckenzie and Pegram, 1993), has now been replaced by a new Delphi model called STOCHMOD (van Rooyen and Mckenzie, 2002).

Having developed the necessary pre- and post-processors for the yield model in Delphi together with the stochastic routines, it is now simply a matter of time before a new water resource model is completed which incorporates all of the best features from the WRYM, as well as those from the WRPM and the stochastic models covered by STOCHMOD. It is anticipated that the complete model will be available towards the end of 2002 or during 2003.

CONCLUSIONS

Considerable development in the field of water resource management has taken place in South Africa over the past 20 years. While it is rarely possible or desirable to transplant analysis techniques from one country to another, the methodology used in South Africa has been developed in such a manner that it is appropriate to a wide variety of climatic conditions, particularly in arid and semi-arid areas. Any water resource managers considering the development of a new water resources model can gain considerable insight from the South African experience and may be able to avoid some of the painful pitfalls awaiting them. Certain components of the South African water resource modelling techniques may be of use in Australia and parts of Asia with minimal modification which in turn can save several years of development time. Most of the software and the analysis techniques are well documented and available in the public domain with the result that they can be used by other individuals and organisations if desired.

ACKNOWLEDGEMENTS

The authors of this paper would like to acknowledge the support of the South African Department of Water Affairs and Forestry over an 18 year period without which the various developments discussed in this paper would not have materialised. In particular the vision and support of Mr Johan Van Rooyen from the Directorate of Project Planning was instrumental in the developments and success of the models. Mr Richard Allan from ACRES International provided considerable support during the first 10 years of the model developments and was always willing to share his knowledge and expertise with the authors. Finally, the authors would also like to acknowledge the support of the South African Water Research Commission (through Mr Hugo Maaren) which has provided financial support to develop the new Delphi versions of the yield model and the stochastic streamflow generation model. Both models will be available through the Water Research Commission towards the end of 2002.

REFERENCES

Allen, RB, 1986a. *ACRES Reservoir Simulation Program : Level 1 Documentation – Introductory Manual*. Acres International, Niagara Falls, Ontario, Canada, 1986

Allen, RB, 1986b. *ACRES Reservoir Simulation Program : Level 2 Documentation – Reference Manual*. Acres International, Niagara Falls, Ontario, Canada, 1986

Basson, MS, Allen, RB, Pegram, GGS and Van Rooyen, JA. 1994. *Probabilistic Management of Water Resource and Hydropower Systems*. Water Resource Publications, USA, ISBN, 918334-89-6, 1994.

Jensen, PA and Barnes, JW. 1980. *Network Flow Programming*, John Wiley and Sons Inc.

Mckenzie, RS and Allen RB, 1990. *Modern Water Resource Assessment Techniques for the Vaal System*. Proceedings of the Institution of Civil Engineers, Part 1 pp 995-1014, Dec. 1990.

Mckenzie, RS and Van Vuuren, SJ, 1989. *The Impact of Catchment Developments on River Basin Response*. Proc. of the South African Institute of Civil Engineers, Oct. 89, pp 349-353.

Mckenzie, RS and Pegram GGS, 1993. *GENMAC: User Guide*. Report to the South African Department of Water Affairs and Forestry by BKS Pty Ltd – Number P3464/02/07, 1993.

Mckenzie, RS and Van Rooyen PG, *Water Resources Yield Model: User Guide Release 4.1.1.* Report to the South African Department of Water Affairs and Forestry Number P C000/00/001/98, Private Bag X313, Pretoria 0001, South Africa, 1998.

Sigvaldason, OT, 1976. *A simulation Model for Operating a Multipurpose Multi-reservoir System.* Water Resources Research, Volume 12, Number 2, April, 1976.

van Rooyen, PG and van Rooyen, JA, 1993. *Inter Basin Transfer Management and Planning as Implemented in the Vaal River System*. Sixth South African National Hydrological Symposium, Volume I, 8-10 November 1993.

van Rooyen, PG and Rademeyer JI, 2000. *Development Planning of the Integrated Vaal River System*, Vaal River 2000 conference, Johannesburg, 7 & 8 November 2000.

Van Rooyen, PG and Mckenzie, RS. 2002. *STOCHMOD: User Guide*. Report to the South African Water Research Commission (in preparation to be released in 2002).

CONTACT DETAILS

R S Mckenzie
Water Resource Planning Pty Ltd.
PO Box 1522,
Brooklyn Square, Pretoria,
South Africa, 0075
Tel : +27 12 346 4483
Fax : +27 12 346 6006
Email : ronniem@wrp.co.za

P G van Rooyen
Water Resource Planning Pty Ltd.
PO Box 1522,
Brooklyn Square, Pretoria,
South Africa, 0075
Tel : +27 12 346 4483
Fax : +27 12 346 6006
Email : pieterv@wrp.co.za