Chapter 8

Development and use of a water systems analysis model

8.1 Introduction

In South Africa, system analysis in surface water resources is addressed using simulation models such as WRYM, WRPM, WRSM90, ACRU and SHELL. The models used for the initial simulations in systems analysis, that is WRSM90 and SHELL, are simply improved versions of the Pitman model, a monthly time-step Rainfall-Runoff model that has been successfully used in southern Africa for at least 30 years. Most of the water resources system analysis models used in South Africa today were developed in the mid 1980s to early 1990s. Changes in the software industry have seen the increased dominance of programming languages that are compatible with the OOP and the Windows environment replacing the outdated command-line type software such as the BASIC and the older versions of FORTRAN. The use of applications developed in Basic and the 1995 version of FORTRAN or older comes with many disadvantages. These disadvantages include the lack of visual interface controls, difficulty in remembering of text commands and loss of many man-hours in non-productive tasks associated with poor user support. In most of this command line programming software, users have no access to error pointers and guidance on methods for resolving these errors. It is therefore advantageous to have model developments that are based on more modern or recent releases of programming languages such as C++, Visual Basic, Delphi, Java and COBRA. The use of old software to solve today's problems comes with many disadvantages, it is well described by Timperley (2000) when he says, "Struggling to do things in ways that aren't now effective is like travelling at 80 miles per hour in second gear; it's a rough ride and immensely wearing on the system".

The model HYDRO25 was developed as a result of the author's appreciation of the modern IT environment and the need to accommodate common preferences in Windows applications, as well as an interest in investigating model applications in water systems analysis. In the model HYDRO25, the emphasis has been to develop user interfaces that are closely related to existing Windows application interfaces, especially the Microsoft packages that are most commonly used in southern Africa. The model development process also placed great emphasis on the need for error handling, provision of user feedback and walking the user through the modelling process by using dialog boxes, error handling routines and informative changes to the user controls.

8.2 Why the model HYDRO25 was developed

The theoretical assessment of local model development and use was extended to a practical approach through the development and use of the model HYDRO25. The model HYDRO25 was developed to simulate a water resource system using mathematical formulas that have been developed and tested over time in South African catchments. These mathematical simulation formulas were adapted for the HYDRO25 model and linked to other water management tools consisting mainly of hydrological data analysis and formatting tools, as well as graphical and mapping objects. The observations and experiences gained in the case study on model development and use were used to improve modelling guidance and recommendations. The model development also served as a case study in which observations and issues identified in the theoretical research were tested and applied to real life modelling problems.

The name of the model, HYDRO25, was coined from an initial model that used 25 mathematical functions to carry out hydrological simulations in a spreadsheet. The development of HYDRO25 aimed to eliminate the difficult-to-remember text commands used in applications based on command line software languages. Treu (1994) pointed out that the command line interaction is of little excitement or demand to the user's sensory mode. Treu (1994) also found that many industrialists were shunning the computers in their work environments because of the poor sensory excitement they offered. The water industry, which also utilises computer applications, was equally affected by the command line software languages. In HYDRO25, the idea behind the use of a graphical interface is to make the user visualise and conceptualise the computer-aided solutions. The images and graphics displayed by the application provide visual representation of the physical and logical patterns in the water resources system in a way that is consistent with the mental picture generated in the human mind. Treu (1994) mentions that computer applications that fail to fulfil conditions, demands, desires, and hopes in a user's attempts to reach a goal are a source of work related stress. In this study, sources of computer dissatisfaction were identified and a concerted effort was made to eliminate them through the development of HYDRO25.

The model HYDRO25 links together several important developments that have been achieved over the years in hydrological mathematical formulations, modelling solution development, graphical user interfaces within a Windows environment, using improved, larger and faster computing resources and improved software that enhance application connectivity. The model HYDRO25 provides all the benefits of the Windows computing environment, such as a familiar and user-friendly desktop environment, convenient data transfer to and from other Windows applications via object linking and embedding (OLE). In the Windows environment, HYDRO25 also benefits from the readily available access to a wide variety of display and printer drivers, and efficient utilisation of computer resources, such as disk space and extended memory. The language VB6 used to develop HYDRO25 allows for communication with other Component-based applications, utilising their functions and properties to give more freedom to their user when tackling a problem, as well as providing greater application control and a variety of analytical methods that the user can deploy to meet his/her objectives.

In developing the model HYDRO25, the developer sought to bring modelling within the reach of all water sector stakeholders through an easy to use application that merges easily with widely used software.

8.3 The general model structure

Water resources systems exist in many spatially different forms that are dictated by natural and anthropogenic factors. The existence of flat terrain, lakes, steeply sloping rivers, wide meandering channels, water storages, mountains and other physical characteristics that are not easily controlled by man cannot be reasonably included in models such as HYDRO25 without dramatic increases in model complexity. The different physical characteristics of a catchment, and how they are connected with the hydrology and time, constitute a water resources system. To analyse different types of systems, the model HYDRO25 has been developed using a modular concept where the user chooses component modules that best describe his/her system, then arranges them in a way that relates to the time or sequence in which the activities represented by each module occur. In this study, the terms module, sub-routine or sub-model, will be used to refer to the basic component of the modular structure used in the model development. A module contains a collection of interconnected mathematical functions or code-defined procedures that will generate an output that is either available to the user, or to another module for use in another process. The ideal situation in systems analysis modelling will be a model that accounts for all the catchment characteristics and gives accurate accounts of how each drop of water goes through the water system. Model development is achieving ever finer levels of detail, with hourly time step simulations being a reality in some models such as Mike-SHE (DHI, 2000). The general trend has been to identify the more dominant characteristics in the catchment and to write software that simplifies these characteristics using proven theories of water management, hydrology and hydraulics, as well as existing data for the area under consideration. These same ideas have been used in the development of HYDRO25. A monthly time step was selected for the model to accommodate a number of factors, which included the availability of data in this time resolution, the type of information that was required from the simulation process, the planning processes that were targeted to benefit from the model, and the availability of resources to deal with monthly time steps in terms of theories, time and experience. The HYDRO25 model includes the following processes: rainfall, interception, evaporation, seepage, runoff on the surface, in rivers and channels, accumulation of water in storages, and water spillage and releases from storage reservoirs and its subsequent application for irrigation purposes.

The model has six main modules. Appendix A1 of this study provides a detailed description of the model modules and interfaces. The main modules in HYDRO25 are illustrated in figure 8.1 which also shows the module linkages and connectivity to user interfaces. A list of these modules and brief module explanations follows figure 8.1.

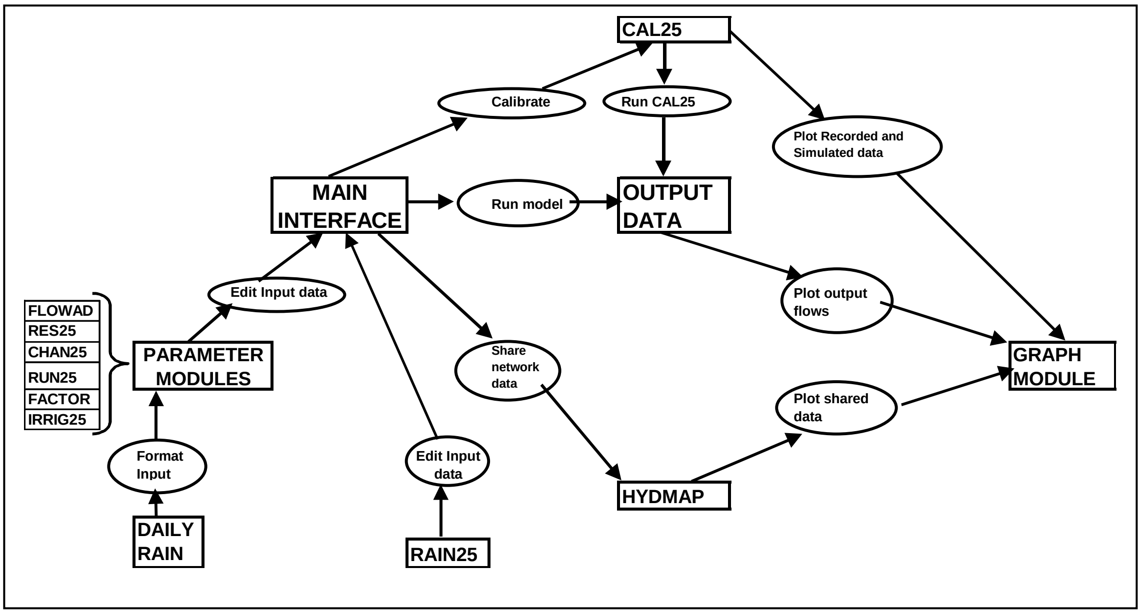

Figure 8.1 HYDRO25 flow diagram showing the main modules linkages.

- RUN25 : Rainfall/Runoff simulation
- RES25 : Reservoir water balance simulation
- CHAN25 : Accounting for channel losses and aquifer recharge
- IRRIG25 : Evaluation of irrigation water demand based on crop factors, irrigated area, irrigation efficiencies, rainfall, evaporation and other factors
- FLOWADD : Addition and subtraction of flows from different modules.
- FACTORFLOW : Separation of flows into components in cases such as when a quantity of water released by a dam is directed for different uses

In the model, five other input and output support modules have been included for other useful stand-alone functions. These modules are:

- RAIN25 : for use in generation of monthly rainfall percentages of the MAP that best represents the catchment being modelled, the main input in the simulation.
- Daily rain : used in formatting daily rainfall data such that they can be used as input in the RUN25 module.
- CAL25 : used in the calibration of the rainfall-runoff simulation against recorded runoff to give the best parameters for use in the simulation.

- GRAPH : gives graphical illustrations of the flow data to improve the user's visualisation and conceptualisation of the physical catchment.
- HYDMAP : allows integration of the mathematical functions, catchment data and model code to the catchment map to give a sense of virtual reality to the user.

8.4 An overview of model modules

The model HYDRO25 is made up of graphical user interfaces (called forms or windows) and the model modules. Blocks of computer code, also referred to as module code, which are attached to each form, are linked to a common interface from which all communications between the model user and the model are initiated. The user communicates with the model through his/her actions on the form interfaces. These actions, which are referred to as events, include clicks, movement of the computer pointer and pressing of computer keyboard characters. The model modules provide user feed-back through displayed messages, graphical changes on module controls, enabling or disabling certain events, and sometimes audible clicking sounds. When using the model, the user will select the form that he/she wishes to work on from the main user interface. The use of a number of forms was chosen as a way to group processes, inputs and events that are linked to particular outputs, such as calibration of rainfall-runoff processes or entering irrigation inputs. It was found advisable to limit the number of controls on each form to a maximum of 254 and that blank spaces should be used between and around controls to avoid cluttering the interface (Eric, 1999). The developer also noted the strain that large forms with many controls made on different computer resources, with cases where some computers were overwhelmed by a single form's memory requirements.

When simulating the linked code modules under the "Run" command, the different code blocks are called to execute their actions at intervals specified in a network file using call procedures. The network file also supplies the information on the specific parameter file that will be used for each sub-routine. The model does not use the values on the interface to run a simulation, rather it runs simulations from the most recently saved files. This allows the user to be able to work on saved data and also to know which inputs produced which results in cases where many simulations will be executed. The use of data saved in files to run the model facilitates the possibility of using a two-tier system for the modelling process, where the user can use an Internet or network browser to access the model code and data stored in a remote server. A modelling system on a two-tier platform such as this improves model accessibility and expands the use of memory capacity of remote computers, as well as allowing them to benefit from other functions that are not available on the local server.

A more detailed account of the model development process, input data collection, analysis and model set up is presented in Appendices I and II, while the model verification and calibration process is discussed in Chapter 9 of this study.

Chapter 9

Doring River catchment simulation, calibration and verification

9.1 Introduction

The water resources development options in the Doring River catchment were evaluated to provide information on the impact of various proposed developments of dams and irrigation schemes. The objective of the case study was to utilise the most up to date hydrological data and include the most recent development proposals to conceptualise, analyse and evaluate different development options that would support and sustain economic growth, using the water resources model HYDRO25. The economic activities in the area are predominantly agriculture oriented, resulting in the identification of water development options aimed largely at sustaining existing irrigation practices and the expansion of large-scale irrigation schemes. Water demands by other sectors such as domestic and industrial use had no noticeable effects at the scale of volumes considered in this study as they consumed less than 1 million cubic metres per annum out of an annual average of 240 million cubic metres of surface water in the catchment. Domestic and industrial use of water is projected to decrease drastically in future with decreases as high as 30 % in some areas due to urban migration and farm mechanisation (DWAF, 2001b). In this study, the simulations placed particular emphasis on the irrigation demand, water reserve and environmental water uses, all of which have major effects on the catchment hydrology. Appendix A2 of this study provides further information on the data collection, analysis and model data entry for the Doring River case study.

9.2 The study area

The case study was based on the Doring River catchment, shown in Figure 9.1, a tributary of the Olifants River in the Western Cape Province. The Olifants River is located approximately 170 km downstream of gauge E2H002 which is further north of the gauge position shown in the Map (Figure 9.1). The study area consists of the Groot, Doring and Riet River subsystems, which cover 6,888 km^2. The catchment straddles the divide between winter and summer rainfall regions. The Southeast corner of the catchment forms part of the Koue Bokkeveld, a generally mountainous region with winter annual rainfall in excess of 500 mm annually. The MAP decreases to around 200 mm of mainly summer rainfall in the north of Ceres Town. The winter rainfall falling in the mountainous areas dominates the seasonal variation of run-off in the Doring River.

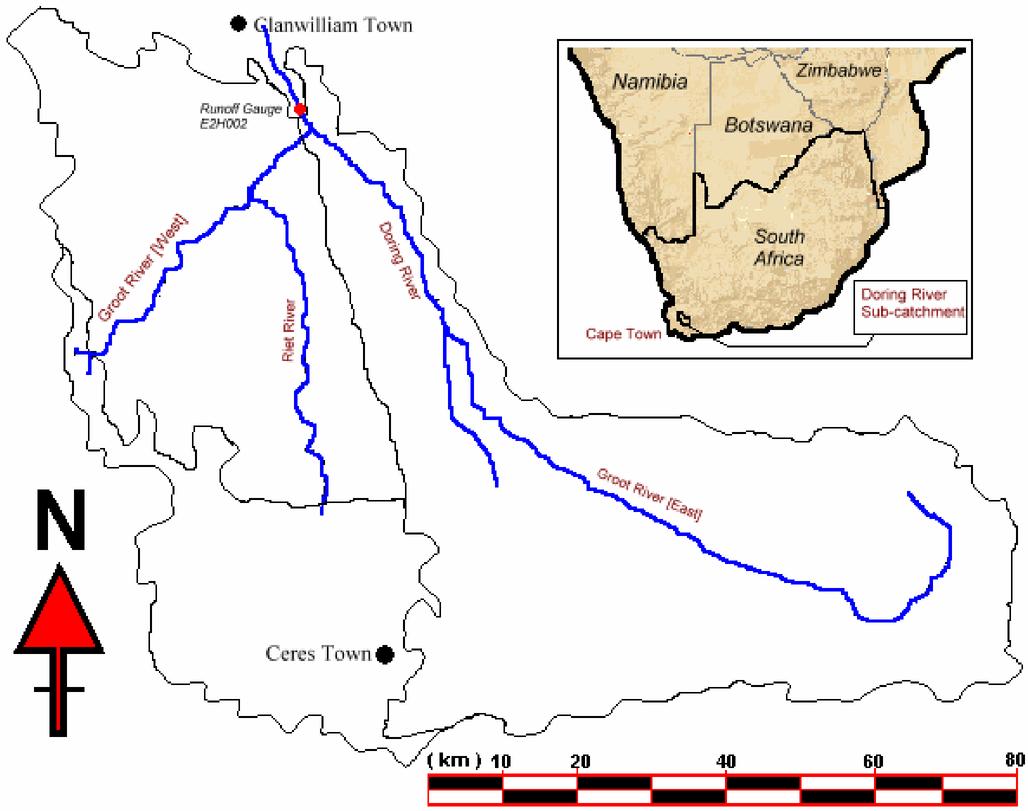

Figure 9.1 The study area (Insert map shows location in Southern Africa).

9.3 Water use activities in the Doring catchment

The Doring catchment is dominated by irrigation uses. Studies carried out by DWAF (Theron and du Plessis, 1998) have indicated that the Doring River catchment has 53,000 hectares (ha) of suitable irrigable soils, though only 11,000 ha have been developed to date. Present irrigation development is concentrated in the Koue Bokkeveld (KBV) area where 9,000 ha have been developed out of the 36,000 ha identified as irrigable in this area. Development proposals are targeted for the KBV area where up to 3,650 ha irrigation land expansion is being considered in short-term plans. Irrigation in the KBV area utilises 30 % of the flow of the Groot River before its confluence with the Doring River.

The other important scheme under consideration lies in the Aspoort area, where a total of 3000 ha is earmarked for development in the Aspoort irrigation scheme. Only 350 ha are presently being irrigated in the Aspoort area at Elandsvlei. A dam development at Aspoort has been proposed to support the proposed Aspoort irrigation scheme. The development of the Aspoort scheme depends on the amount of irrigation development that will take place in KBV as the two schemes will share the same water resource. Locations of the proposed irrigation schemes are shown in Figure 10.1 of this report.

The main crops grown in the KBV area are deciduous fruits, while citrus, vines and vegetables with low water requirements such as cabbages, are preferred in the Aspoort irrigation area. The proportion of the main crops grown in the Doring catchment are shown in Table 9.1, while Table 9.2 shows the crop factors based on Green (1985) for the crops grown and/or proposed to be grown in the irrigation schemes of the study area.

Table 9.1 Extent of crops grown in the present irrigation schemes.

KBV sub-catchment		**Aspoort sub-catchment**	
% of area	**Crop type**	**% of area**	**Crop type**
15	Apples	5	Vegetables
5	Pears	5	Vines
5	Peaches	5	Citrus
15	Vegetables	15	Pasture
60	Pastures	70	Lucerne

Table 9.2 Irrigation crop factors for major crops grown in the case study area.

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Vegetables	0.8	1.0	1.0	1.0	0.5	0.5	0.5	0.5	0.5	0.5	0.5	0.5
Pasture	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.5	0.5	0.5	0.6
Lucerne	0.7	0.8	0.8	0.8	0.8	0.8	0.7	0.6	0.5	0.5	0.5	0.6
Vines	0.3	0.4	0.5	0.5	0.5	0.5	0.2	0.2	0.2	0.2	0.2	0.2
Apples	0.3	0.4	0.5	0.6	0.6	0.5	0.2	0.2	0.2	0.2	0.2	0.2
Pears	0.3	0.4	0.5	0.6	0.6	0.5	0.2	0.2	0.2	0.2	0.2	0.2
Peaches	0.3	0.4	0.5	0.6	0.6	0.5	0.2	0.2	0.2	0.2	0.2	0.2
Citrus	0.3	0.4	0.5	0.5	0.6	0.5	0.2	0.2	0.2	0.2	0.2	0.2

The development proposals for the Doring River system are centred on the existing two irrigation schemes, namely the KBV scheme and the Aspoort scheme. DWAF and the stakeholders in the Doring catchment, are seeking information on a number of factors important for decision making in the catchment. The information requirements are centred on two main issues: (1) determining the maximum amount of irrigation that can be carried out in the KBV scheme without the Aspoort scheme or additional storage, and (2) determining the best option for development of both the KBV and Aspoort schemes with and without a dam at Aspoort. In this study only the hydrological implications were evaluated using the model HYDRO25. Apart from the hydrological considerations, it is important to note that several other issues also require considerable attention. These include the assessment of the economic, social and financial factors, as well as an evaluation of the concept of virtual water, where the idea is to irrigate those areas which are most favourable for the growth of plants without straining the system or the means. Studies on virtual water transfers in Israel have shown that that country's economy improved when it utilised virtual water transfers by buying grain from other countries with favourable climates (Nyagwambo and Savenije, 1998).

9.4 Simulation scenarios

This study aimed to provide decision-makers in the upper Doring River system with information on the implications associated with different irrigation development options. The options were solved as scenarios of possible development options, and were segmented as follows:

1) How much additional land can be put under irrigation in the KBV area without additions to the existing storage in the area. The irrigation will benefit from river runoff from the relatively higher rainfall south-western parts of the catchment.
2) Determine the best combination of additional irrigation in the KBV and Aspoort catchments that utilise most of the available 3,000 ha at Aspoort. The KBV scheme proposes to use runoff only as in (1), while the Aspoort scheme will utilise the water stored in the proposed (new) 178 million m^3 capacity dam.

The simulation scenarios sought to use the most up to date hydrology data and to update the existing information on land use development and other water-using activities, such as the In-stream Flow Requirements (IFR), that have become mandatory in terms of the National Water Act (Republic of South Africa, 1998).

9.5 Simulation stages

9.5.1 Creating the water system network and data entry

In the HYDRO25 model, the catchment was schematised using the different modelling modules as shown in Figure A2.8 of Appendix A. Each module was defined for the simulation using data and parameter input files named in such a way that one can easily remember the modules using different files. Table 9.3 illustrates the modules and input files used in the Doring River system. Appendices A1 and A2 provide further details on the HYDRO25 model data entry and use.

The catchment was subdivided into two sub-catchments, a higher rainfall sub-catchment with an MAP of 553 mm, and a drier sub-catchment with an MAP of 269 mm (Figure 9.2). In this scheme, the drier catchment is referred to as the Aspoort sub-catchment while the wetter sub-catchment is the KBV sub-catchment. The catchment divisions (Figure 9.3) are based on boundaries used in previous studies of the area (McKenzie, Schafer and Venter, 1990; Theron and du Plessis, 1998). These catchment divisions were used in the model calibration.

Table 9.3 Doring system network as displayed in the main user interface.

	Module	Input file1	Input file2	Input file 3	Main output
1	RUN25	sub1.ran			RRkbv.flo
2	IRRIG25	sub1.ran			Irkbv1.dem
3	RES25	RRkbv.flo	IRkbv1.dem		Dkbv1.rel
4	FLOWAD	Dkbv1.rel	IRkbv11.ret		kbv1.flo
5	IRRIG25	sub1.ran			Irkbv2.dem
6	RES25	kbv1.flo	IRkbv2.dem		Boukkeveld.rel
7	RUN25	sub2.ran			RRAsp1.flo
8	FLOWAD	RRAsp1.flo	Boukkeveld.rel	IRkbv21.ret	Adasp1.flo
9	IRRIG25	sub2.ran			Irasp1.dem
10	RES25	ADasp1.flo	IRasp1.dem		Dasp1.rel
11	FLOWAD	Dasp1.rel	IRasp11.ret		Adasp2.flo
12	IRRIG25	sub2.ran			Irasp2.dem
13	RES25	ADasp2.flo	IRasp2.dem		Aspoort.rel
14	FLOWAD	Aspoort.rel	IRasp21.ret		Adasp3.flo

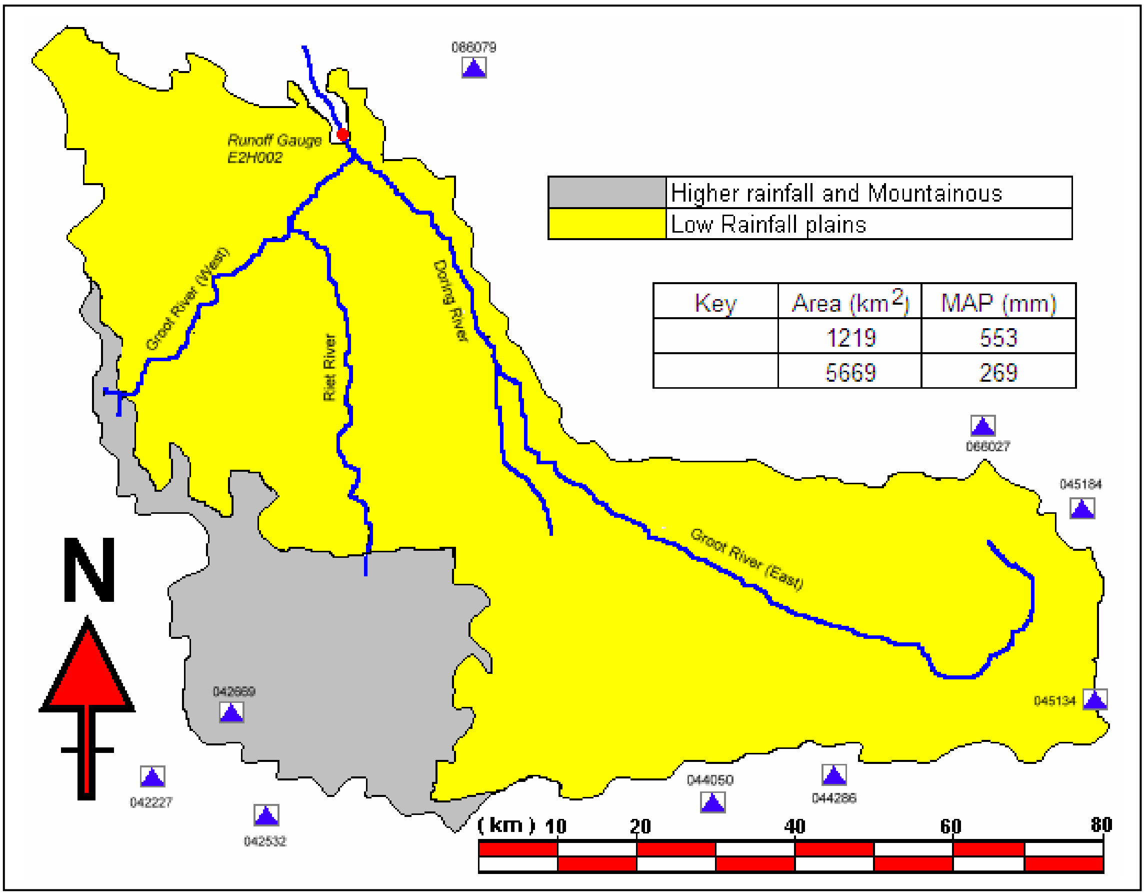

Figure 9.2 Doring River system catchment divisions based on mean annual rainfall distribution, and showing positions of rainfall gauging stations used in this study.

In the model, the KBV area was composed of 1,219 km^2 of the high rainfall area with an MAP of 553 and 1,829 km^2 of lower rainfall area on the Groot River as shown in Figure 9.3. The two areas were simulated using a lumped catchment with an MAP of 383 mm. In the simulation, separation of these areas into subcatchment was not possible because of the absence of separate runoff records. The other area, referred to as the Aspoort sub-catchment covered an area of 3,840 km^2 and has an MAP of 269 mm.

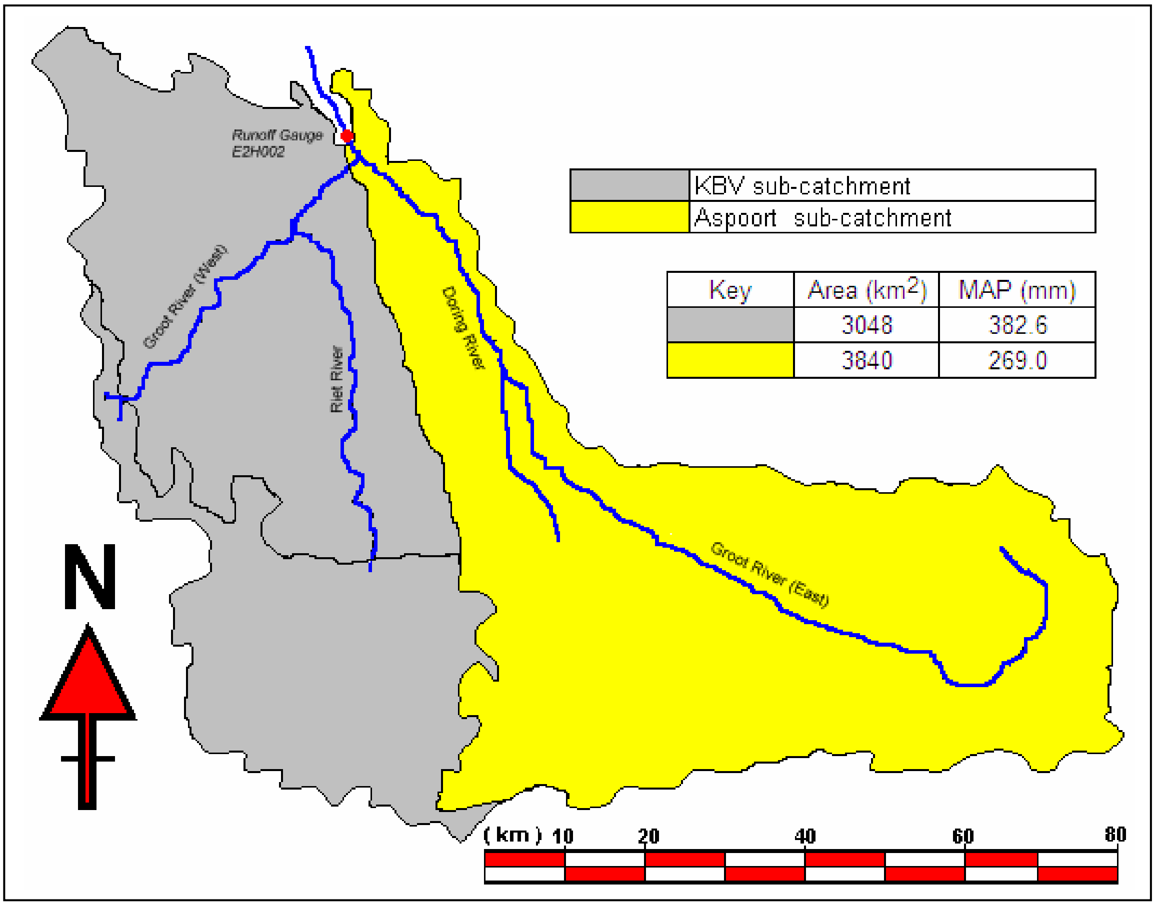

Figure 9.3 The KBV and Aspoort sub-catchments used in simulating historical and proposed developments.

The Aspoort sub-catchment recieved flows from both the KBV area and runoff from its own catchment area. Irrigation in the KBV area is based on the river runoff together with small farm dams that have a combined capacity of 45 million m^3. These farm dams are represented as a "dummy dam" in the first RES25 module. The Aspoort area does not have a large dam and irrigation currently utilises numerous small farm dams with a total capacity of 62 million m^3. In the model, all irrigation was considered to take place from farm dams located on the Doring River system such that they spilled into the Doring River system. The farm dam capacities were added together to produce "dummy dams" in each sub-catchment, where one "dummy dam" was for existing irrigation and another "dummy dam" was meant for the supply of water to the proposed irrigation schemes. Table 9.4 shows the growth in the development of the existing "dummy dams" over time in the KBV and the Aspoort catchments.

Table 9.4 Changes in dam and irrigation development levels in KBV and Aspoort sub-catchments.

Year	1950	1965	1980	1987	1991	1999
KBV Irrigation (km^2)	0.00	10.20	26.88	38.40	44.23	45.00
Aspoort Irrigation (km^2)	0.00	0.56	1.48	2.11	2.43	2.50
KBV Farm dams (Mm^3)	0.00	10.06	26.58	37.97	43.74	45.00
Aspoort farm dams (Mm^3)	0.00	14.28	37.71	53.87	62.08	63.00

Information on irrigation developments was entered in the IRRIG25 module with the average irrigation crop factors being determined on the basis of proposals for the crops to be grown in the schemes. Table 9.5 below shows the distribution of crops on the proposed schemes.

Table 9.5 Present irrigation schemes in the KBV and Aspoort sub-catchment and the extent of crops grown.

KBV sub-catchment		Aspoort sub-catchment	
% of area	**Crop type**	**% of area**	**Crop type**
30	Apples	50	Vines
25	Pears	50	Citrus
25	Peaches		
20	Vegetables		

The average crop factors for each sub-catchment were determined by calculating the total crop area as a percentage of the sub-catchment area then applying the factor as a weighting to that crop's contribution to the average irrigation crop factor. The crop factors for the existing and proposed irrigation were different for two reasons: (1) the crops considered in the two cases were not the same and (2) the crops covered different areas in the two schemes.

Table 9.6 Average irrigation crop factors used to simulate water demand in the KBV and Aspoort sub-catchments.

Existing irrigation												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
KBV	0.58	0.68	0.71	0.73	0.68	0.66	0.52	0.46	0.40	0.40	0.40	0.46
Aspoor	0.67	0.77	0.78	0.78	0.76	0.76	0.64	0.56	0.47	0.47	0.47	0.56
Proposed Irrigation												
	Oct	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
KBV	0.40	0.52	0.60	0.68	0.58	0.50	0.26	0.26	0.26	0.26	0.26	0.26
Aspoor	0.30	0.40	0.50	0.50	0.55	0.50	0.20	0.20	0.20	0.20	0.20	0.20

The increase in farm dam capacity over the simulation period shown in Table 9.4 represents the construction of new farm dams. These dam developments were entered in the RES25 module for the historical simulation scenario. The storage capacities at full development of both schemes were entered for the whole simulation period in those simulations where the viability of schemes in their present state was assessed. The model simulation period was 1925 to 1999 and all data files had to cover this period. The irrigation and farm dams had to start with zero values for the year 1925 because there was no irrigation at that time. The available literature indicated that irrigation started in 1950, (Theron and du Plessis, 1998). To start the irrigation development in 1950, zero start values were entered for the irrigation and the farm dam development for the historical simulation, then the values given in Table 9.4 were entered for the rest of the simulation period.

A number of parameter files were made for each module for the simulation of the different scenarios. Parameter files with entries for irrigation, as shown in Tables 9.4, 9.5 and 9.6, were used to determine the historical performance of the catchment, while the assessment of available water for irrigation of the proposed land had to be assessed as well, with the irrigation being maintained at the proposed irrigation hectarages over the entire simulation period. The monthly A-pan evaporation values which give better representation of evapotranspiration were used in the irrigation module, while Symon's pan evaporation values which are based on open water evaporation were used for the

RES25 and RUN25 modules. Sections 1.8.4 and 2.1.3 of the Appendices give details on the basis of the choice to use different evaporation figures for evaportransipiration and for open water evaporation. Tables 9.7 and 9.8 show the pan-evaporation figures used in the simulation.

Table 9.7 Evaporation figures used in the KBV sub-catchment (mm).

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
A-pan	197	261	310	348	250	227	136	87	63	72	89	125
S-pan	147	200	241	271	197	178	105	65	46	52	64	91
Lake Factor	0.8	1	1	1	1	1	1	1	1	0.8	0.8	0.8

Table 9.8 Evaporation figures used in the Aspoort sub-catchment (mm).

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
A-pan	224	291	340	369	284	249	161	103	70	80	103	146
S-pan	167	221	262	285	222	194	123	77	51	57	74	106
Lake Factor	0.8	1	1	1	1	1	1	1	1	0.8	0.8	0.8

In the water system network, the module FLOWADD was used to bring the return flows from irrigation back into the water system. The simulation in the FLOWADD module involved a simple addition of time series data for water flowing out of the dam and the return flows from the irrigated land. Inputs of the quantities of flow estimated to be returned from each irrigation module were entered in the IRRIG25 module that applied a fixed factor of water supplied to be released by an irrigation area as return flow at monthly time steps. A 10 % return flow factor, based on return flow estimates derived by McKenzie *et al*. (1990) from their work in the catchment, was applied to the irrigation schemes.

9.5.2 Model calibration

In the model, the Rainfall-Runoff Relationship (RRR) was calibrated against recorded data. The calibration process of the RR routine sought to minimise the differences between simulated run-off and the flows recorded at DWAF Stream flow gauge E2H002, which was used in this study. Gauge E2H002 is located at the downstream end of the Doring River catchment (Figure 9.2) such that it measures the combined flows from both the KBV and the Aspoort area. The calibration involved the adjustment of the Rainfall-Runoff parameters which are discussed in Section 1.2.5 of the Appendices, in three steps, namely: (a) selection of calibration period and initial parameter values, (b) preliminary calibration and (c) refined calibration. The use of the module CAL25 in the calibration process is discussed further in Section 1.3.2 of the Appendices.

9.5.2.1 Selection of calibration period and initial parameters

The period 1925 to 1999 was used as the calibration period for the Doring River catchment. This length of record was chosen to ensure the general accuracy of the quantities being simulated over longer periods with little emphasis on the fitness of the records and simulations over shorter periods. Initial parameter selections were based on the *a priori* approach (Schulze, 1998). This approach used the definitions of the parameters, which are discussed further in Section 1.2.5 of the Appendices.

9.5.2.2 Preliminary calibration

In the initial calibration process, manual calibration that aimed to adjust all the parameters was considered. Simulated flows were assessed against the statistical indicators calculated in the model and displayed in the CAL25 user interface. Visual comparisons of monthly and annual hydrographs were used to check for seasonal variations of flows and to monitor general flow trends. The different statistical parameters have different implications in the model outputs. In this study where the primary objective was to assess the hydrological implications of irrigation development potential, the amount of water coming from the catchment, as measured in the calibration process using MAR, was the major indicator of the water available for irrigation. Calibration of the model took into account the importance attached to the different statistical indicators on the basis of the study objectives. Table 9.9 lists the statistical indicators in the order of importance attached to them in the model from the highest, "MAR", to the lowest, "Log Standard Deviation", in the last row of the table.

Table 9.9 HYDRO25 statistical indicators in descending order of sensetivity.

	Statistical Indicator	Definition
1	MAR	Mean annual runoff for the period
2	Wet Season	Average of each year's highest monthly value
3	Dry Season	Average of each year's lowest monthly value
4	Standard Deviation	Standard deviation of annual values
5	Log Standard Deviation	Logarithm of standard deviation of annual values

The order of sensitivity meant that it was most important to ensure that the mean of the simulated runoff, (MAR_s), matched that of the recorded runoff, to ensure that the model did not generate too much or too little water in the catchment. Those statistical indicators with lower sensitivity were more important for fine tuning of other aspects of the simulation, such as variations of flow quantities about the mean value.

9.5.2.3 Refined calibration

Refined calibration was carried out after the parameters obtained in the preliminary calibration gave reasonably good relationships, that is within a 10 % error in the criteria associated to the parameters adjusted in the calibration. The main criteria used in calibration were: a comparison of the mean, wet and dry season values, standard deviation and log of standard deviation for the simulated and recorded flows. The refined calibration involved fine-tuning of the parameter values using mainly automatic processes within the model. Automatic calibration is discussed in this report in Section 9.5 as a process where the model goes through a user defined loop varying a single parameter at a time to meet specified targets for the statistical parameters as set by the modeller. Whilst the fine tuning method was fast, it is not based on the physical nature of the catchment. It relies strongly on the objectives set for the output such that there was need to bring all the parameters within a 10 % error margin before using the automatic calibration. The 10 % error margin meant that the statistical indicator obtained for the simulated flows is not more than 10 % greater or smaller than the same indicator in the recorded flows.

9.5.3 Verification of model performance

9.5.3.1 Introduction

The verification of the model HYDRO25 aimed to establish the consistency of the simulations with the physical behaviour of the catchment. Model verification was performed in the environment that the model would be expected to be used, that is the water resources system with large irrigation schemes, where the irrigation is based on surface water supplies. In the verification process, the performance of internal state variables was evaluated and, in some cases, the coding had to be adjusted to correct some undesirable situations such as shortcomings in the coding of mathematical formula that were highlighted in the verification process. Verification was therefore a part of the model development process where each functional block of the model was tested with measured data to assess how it would perform in different circumstances resulting from the data used. Such, situations included: high summer rainfall, high winter rainfall, short-term data inputs of up to ten years and longer term rainfall data of at least 30 years. In the process of model verification, goodness-of-fit criteria, or objective functions, were set using known water flow record characteristics to give a measure of how satisfactory the model components were performing.

9.5.3.2 Objective functions

Each of the model modules had different objective functions that were related to the main events occurring within the specific module. The objective functions involved comparisons made through visual assessments, in cases where graphical observations were used to verify the model, and in most of the cases, the verification depended on mathematical functions which expressed the most desired characteristics of the simulated outputs when compared to the physical behaviour in the catchment. In the rainfall-runoff module the parameters used as the objective functions were the same as those used in calibration (Table 9.9). In this case, however, inputs from other catchments were also applied to determine how the model behaved with them. It was not possible to give all the statistical indicators the same level of importance/weighting and allow the same degree of fit in all cases, because other external factors such as lumping of the catchment into one unit limited the accuracy of recorded rainfall data. In addition to the problem resulting from catchment lumping, interrelationships between the parameters made the sensitivity of the statistical indicators to parameter changes very different. In the rainfall-runoff module, the mean annual runoff was considered most important and had to match that of the natural system for the historical simulations. In the reservoir and channel module, the most important objective function was based on the water balance. The water balance equations used in the modules, (given in Sections 1.2.2. 1.2.3, 1.4.2 and 1.5.1 of the Appendices), had to give an accurate module water balance. In the irrigation module, the quantities of irrigation demand generated by the module had to match the values given in the literature for the catchment (Green, 1985).

9.5.3.3 Visual observations in verification

The use of graphical plots to verify the model was applied mainly to the main output files specified by the user in the main user interface of the model. In the graphs the model calculations could be assessed through examination of the output files on their own, or compared with observations in cases where such observations were available. Section 10 of this study shows several graphical plots of the output of irrigation calculations as a time series event.

In Figure 9.4, the output corresponds closely to expected monthly volumes of water demand when compared to the extent of irrigation area in each year, as given in Table 9.4, for the KBV area. The irrigation module in this case is observed to have calculated irrigation water demand according to the inputs. The irrigation module was also assessed using a water balance calculation that was built into the model for monthly calculations.

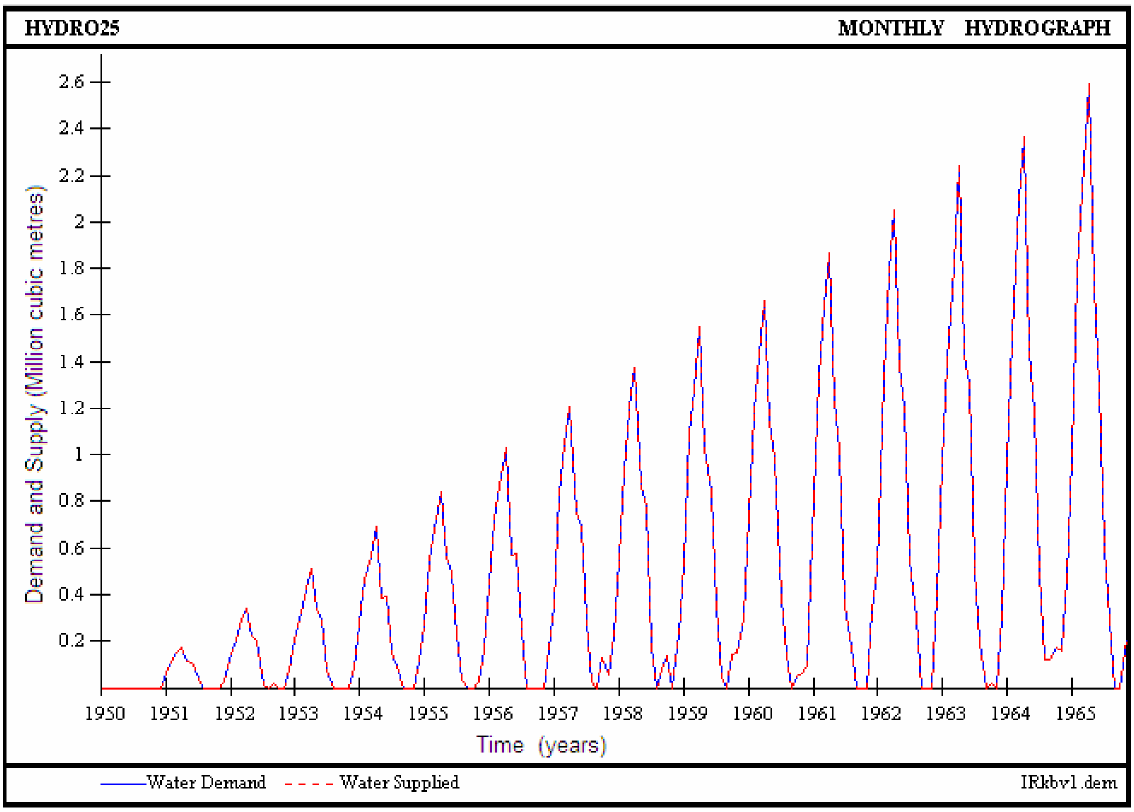

Figure 9.4 **An example of a graphical plot used in visual evaluations of model performance.**

Figure 9.5 shows the observations made in the rainfall-runoff simulations. In Figure 9.5, recorded flows at gauge E2H003 were plotted against simulated flows for the same time period. The simulated flows were observed to have a general trend in flow volumes that related closely to the recorded flows for most of the period (Figure 9.5). Monthly flow variations were verified through the simulation of the rainfall-runoff process, first alone and then with the Doring catchment lumped together into one large catchment of 6,588 km^2. In this simulation, accounting for the time related developments in the catchment involved reducing the cathment area producing the runoff, as part of the catchment will now contribute to developed dams. Simulations of the catchment without accounting for developments such as building of water reservoirs gave higher flows in the early years of the simulation, with the lowest flows at the end of the simulation period. In the historical simulation of the catchment, the developments are included in the irrigation and storage modules which are added to the catchment as shown schematically in Figure A2.8 of Appendix A2.

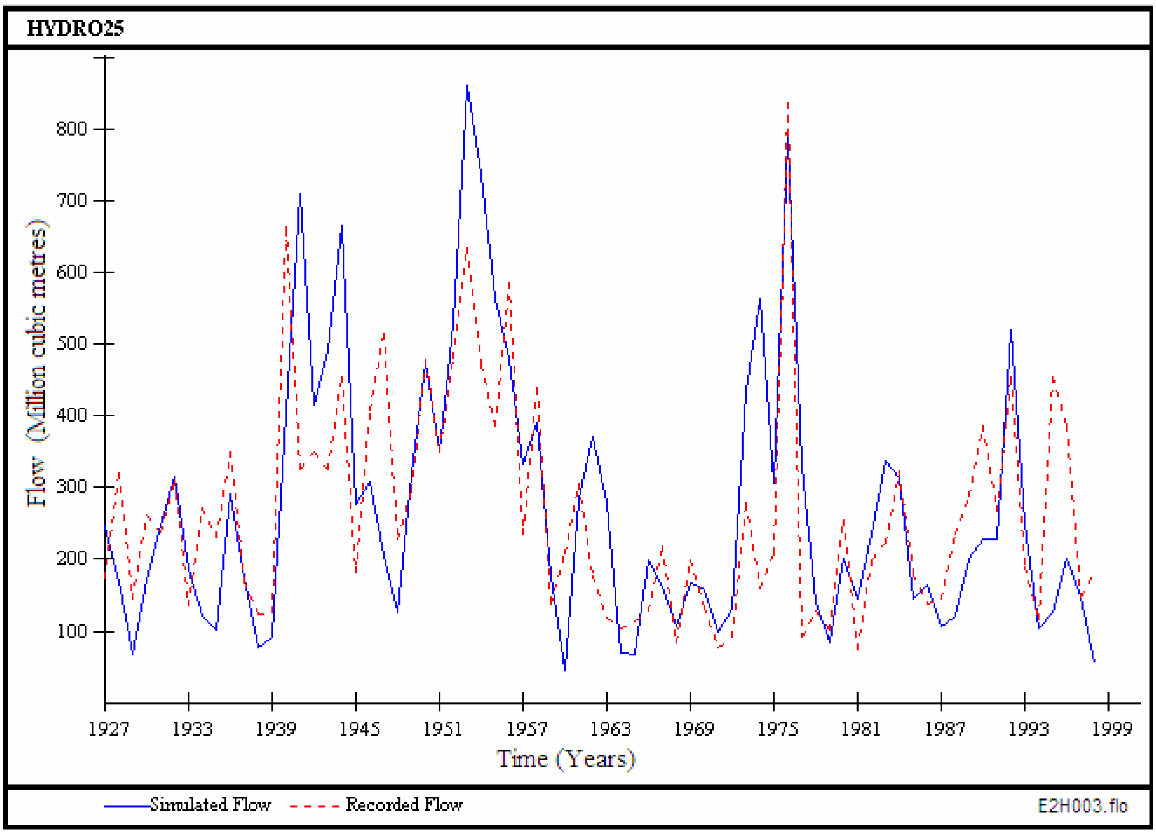

Figure 9.5 Simulated and recorded monthly flows in the Doring River at gauge E2H003.

9.5.3.4 Mathematical objectives in calibration

Mathematical verification involved the use of built-in mathematical functions to calculate statistical parameters, as well as calculations of other statistics such as the percentage errors of objective functions using spreadsheets. The built-in functions included all the statistical indicators used in the calibration of the RUN25 module, (discussed in Section 1.3.2 of the Appendices in this study report), as well as the water balance equations in the modules RES25, CHAN25 and IRRIG25. Verification using mathematical functions was carried out under different hydrological regimes to assess how the model performed in different sets of environments. The historical hydrological data were used in all cases to calibrate the model against observations made in the catchment. The aim in mathematical verification was to determine how the statistical parameters of the generated flows were being affected by the simulations when compared to the statistical calculations in the recorded flows, to find sources of errors and inaccuracies and resolve them where possible. Resolving of errors involved changes to the code in cases where better ideas could be included in the code. Such cases included errors due to poor methods of reading data from files, or incorrectly coded equations in the modules. In some cases, errors were due to incorrectly entered inputs, for example, a wrong MAP entered in the runoff module has drastic effects on the MAR of the simulated flows as well as the errors in flow peaks and troughs.

An illustration of the percentage difference between the simulated annual flows and recorded flows for gauge EH2002 is presented in Figure 9.6. Figure 9.6 shows that the simulated values generally fall in the "fair category" as suggested in Table 6.3 of this report. At least four years have poorly simulated values approaching 80% difference. Some of the sources of errors that resulted in the high levels of differences in simulated and recorded flow values are discussed in Section 9.5.3.5. These sources of errors, especially the poor data resources, could not be completely resolved in this study.

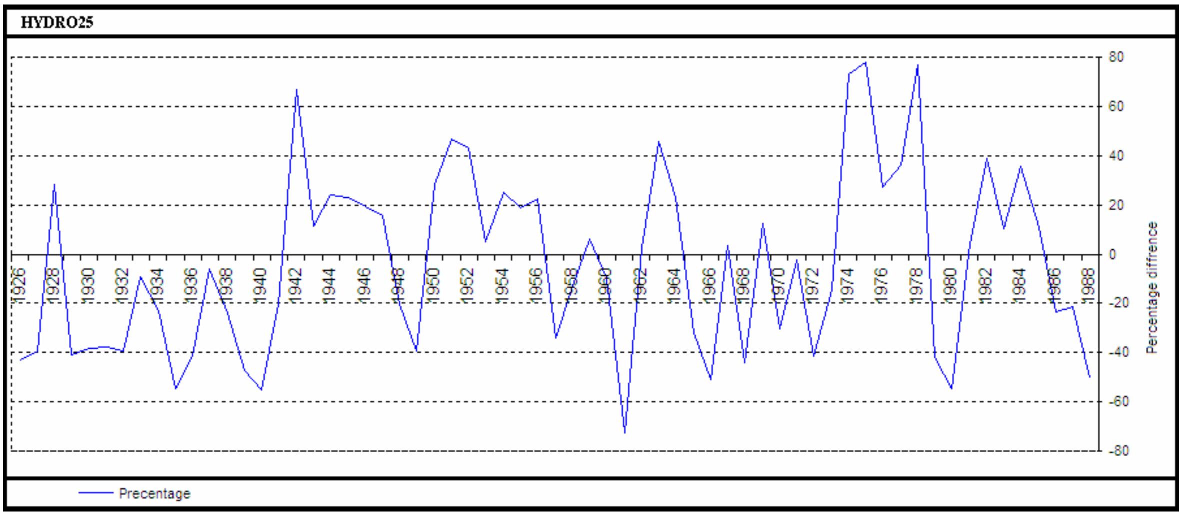

Figure 9.6 Percentage difference between simulated annual flows and recorded flows at gauge E2H002.

The verification process tried to look at all parameters without an over emphasis on one aspect, as this could result in an unbalanced approach biased towards only a few aspects of all the events in the model. The model verification showed that the model performance as a whole was very sensitive to the rainfall inputs. The mean of annual runoff came out as the most important objective function where correctness of this function was very important to the overall model performance. The model assessment showed that the model will be very useful in hydrological assessments that involve bulk water flows in catchments, large-scale irrigation and dam development appraisals of similar magnitudes to those assessed in the case study. The model user will be able to use an environment familiar to Windows software users to carry out simulations that are currently dominated by command line software based on DOS-format languages.

9.5.3.5 Sources of error and their identification in verification

In the verification process some model responses did not comply satisfactorily with the selected objective functions in certain situations. Sources of errors of this nature did not need further "massaging", but required that the causes be solved by improvements to the model code and accommodating changes to the simulation methodology where possible. In cases where such measures could not be applied, these areas were identified as requiring further study.

A number of errors and sources of errors were identified in the verification process. Some of these were noted to have the potential to lead the modeller to very difficult situations. They are listed here as follows:

(a) Use of poor rainfall data. In many cases, the problem of poor rainfall data meant that all objective functions could not be met. Runoff generated in the catchment as well as irrigation water provision are driven by rainfall. Without good rainfall data, the modeller lacks the main input to the model and is not advised to simulate runoff using the types of rainfall-runoff simulation routines used in the HYDRO25 model.

(b) Simulation of dry periods or dry catchments. In such cases, it is not possible to set objective functions to use in assessing the quality of the outputs. In cases where good recorded runoff data are available for model calibration, the model can easily be applied to dry catchments, such as the lower Doring River sub-catchment where rainfall averages 269 mm per annum. Catchments with rainfall that is lower than 269 mm per annum have not been tested with the model.

(c) Catchments using a lot of unmeasured groundwater. Flows are affected by unmeasured events in the form of return flows and surface water contributions to irrigation, which prevent comparisons being made between historical simulations and catchment records. In the case of the Doring River catchment investigated in this study there are no quantified records of groundwater use even though Theron and du Plessis (1998) reported of groundwater usage in a few farms in the area.

(d) Lack of runoff gauges of suitable record length or with reliable records. Most runoff gauge records are not accompanied by detailed information about the gauge. In many cases, gauges only measure a certain range of values and exclude low flows or very high flows, which are then most often infilled using estimates, or left as zeros for low flows or as a maximum recordable values for the flood flows. Gaps in the period covered by records are other sources of errors. In the case study investigated in this thesis, Gauge E2H002 has records ending in 1988 (Figure 9.6) while the simulation period stretches to 1999.

Chapter 10

Doring River model simulation results and analysis

10.1 Introduction

The simulations of the historical state of the Doring River system, as well as the development options in the catchment, were done with the catchment subdivided according to the source of irrigation water for each scheme, as shown in Figure 9.3 and Figure 10.1. Figure 10.1 also shows the proposed positions of the dam and the irrigation schemes.

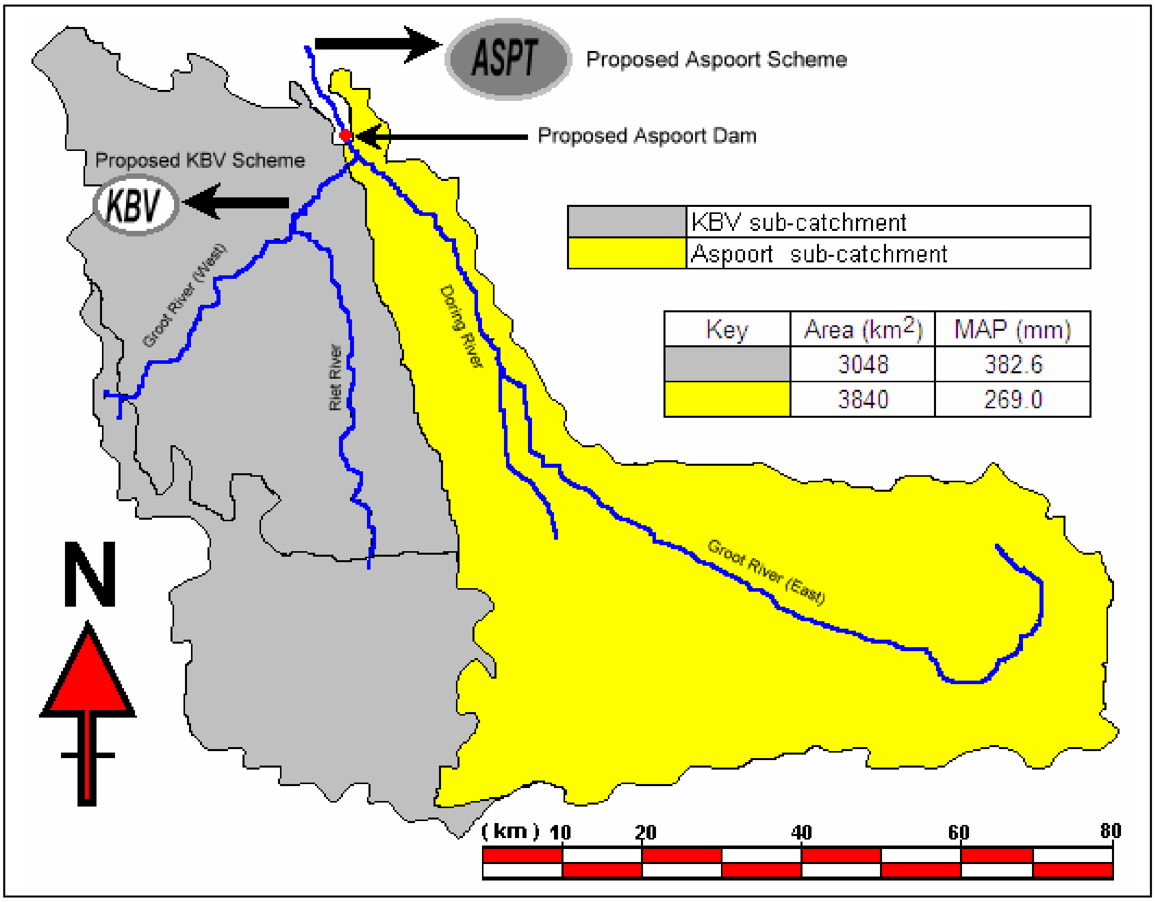

Figure 10.1 Location of upper Doring River system and approximate locations of the associated irrigation development proposals.

10.2 Simulation of historical irrigation patterns

10.2.1 Koue Bokkeveld irrigation

The results of the time series simulation of irrigation water demand and water supply showed that all of the water demand was satisfied over the period simulated, with some small exceptions in 1988 and 1999, when water supply was lower than demand, though still high enough for irrigation purposes as recommended for DWAF projects (BKS, 1986). Irrigation assessments for DWAF is aimed to achieve a water supply level of at least 80 % of the water demand with a risk of failure of 1 in 5 years or better, which translates to a 20 % risk level (BKS, 1986). The 20 % risk level was used as the objective function in assessing irrigation demand in this study. Figure 10.2 shows the irrigation water demand and supply based on the irrigation development trend (Table 9.4 in Chapter 9) from the year 1950 to the year 1999, with the water demand due to the irrigation scheme compared to the quantity of water supplied to meet the demand.

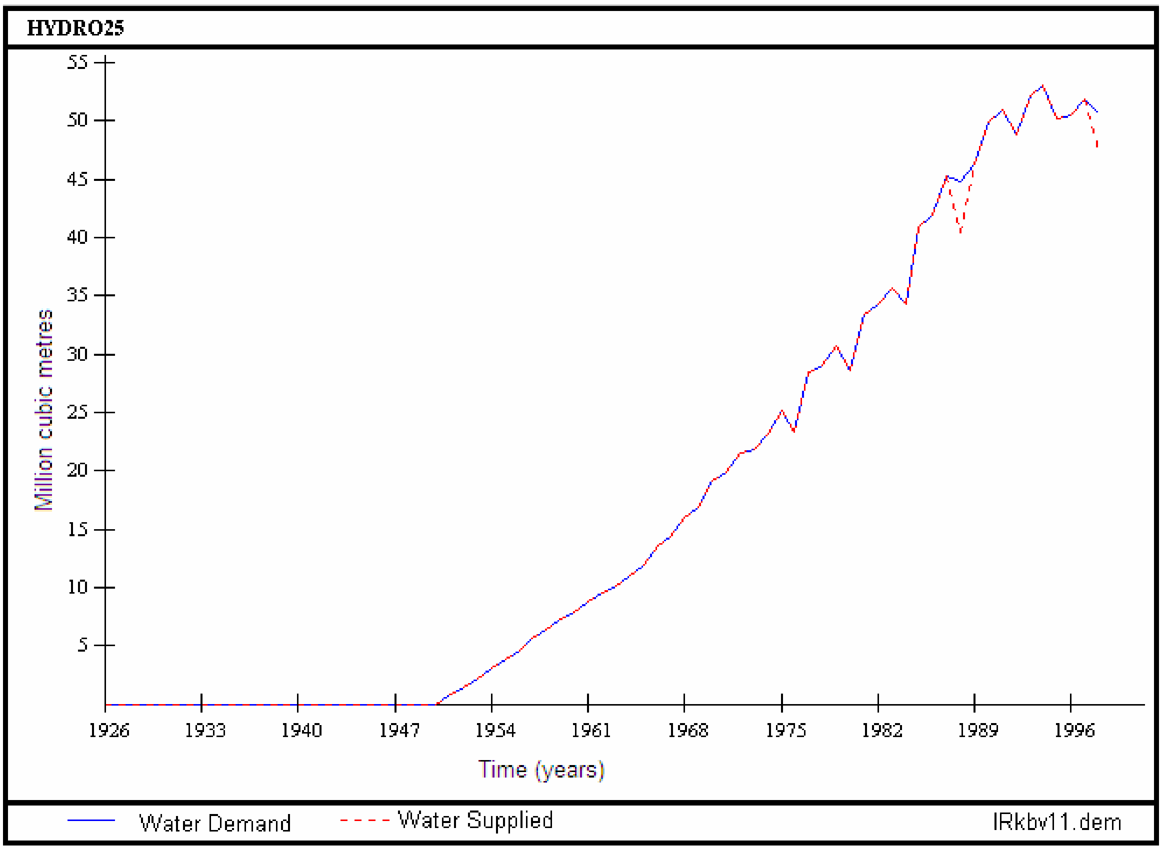

Figure 10.2 Results of simulation of progressive increase in irrigation water demand and quantity of irrigation water supplied between 1926 and 1999.

The irrigation development level and dam development in 1999 was applied over the entire period (*i.e.* maintained constant for the entire period 1925 to 1999) to determine the viability of the scheme in the long-term, assuming that the catchment hydrology does not change drastically. The simulation result shown in Figure 10.3 showed that, for the 75 years simulated, the water supply was an average of approximately 80 % of the demand. These results indicated that the risk of receiving the minimum acceptable quantity of water for irrigation was one in two, without risk of complete failure, which is determined in this model when the water system fails to meet 80 % of water demand. The scheme at the present development level appears to be viable with no detectable risk of a complete failure in any single year.

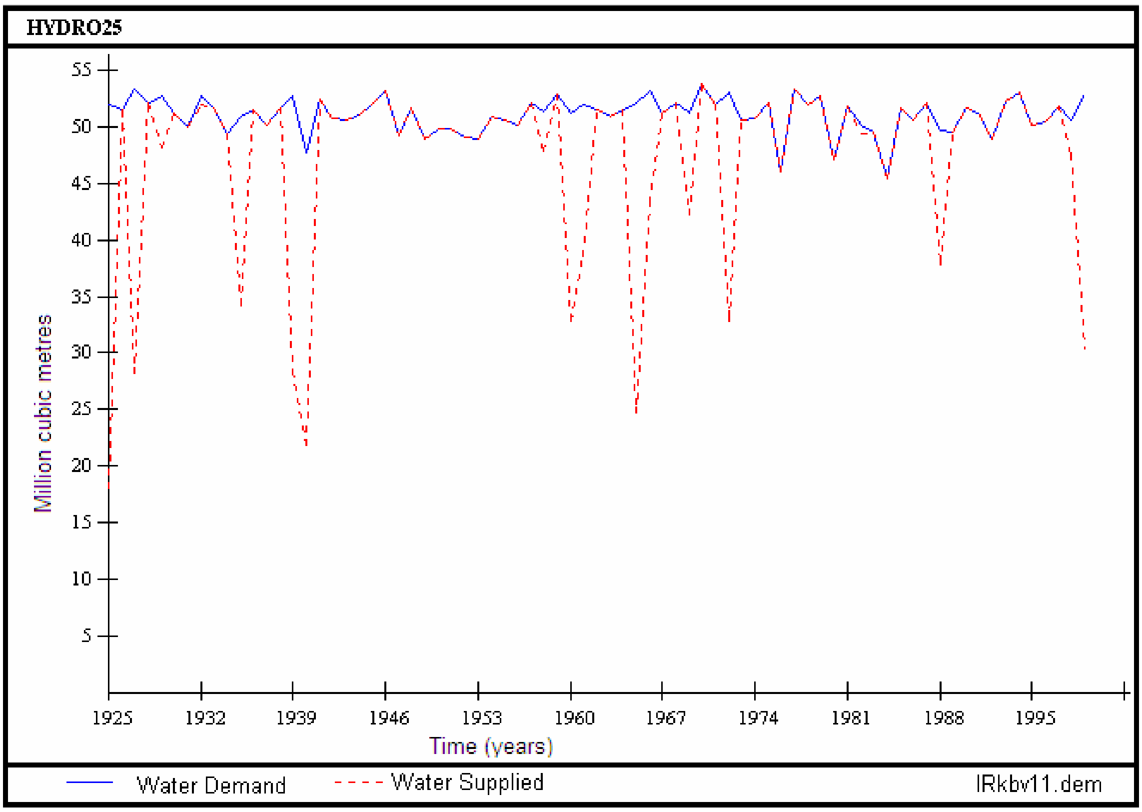

Figure 10.3 Irrigation water demand and supply for the KBV scheme with catchment development in 1999 maintained over the entire record length (1925-1999).

A typical distribution of the long-term average of monthly water demand and supply in the existing KBV scheme is shown in Figure 10.4.

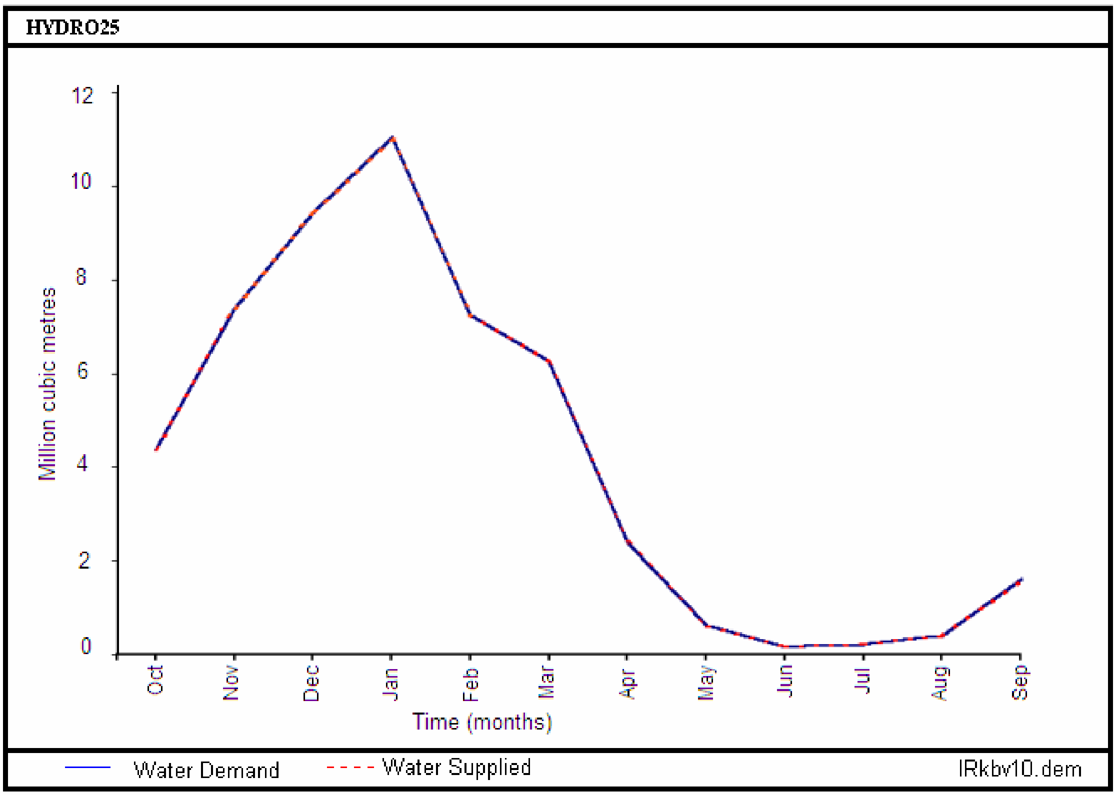

Figure 10.4 Typical monthly distribution of the water demand and supply in the KBV area.

The monthly crop water demand in the KBV area is highest in the period October to March (Figure 10.4). In this same period, rainfall is at its lowest and evaporation is very high, as shown in Table 10.1 for rainfall averages, and in Table A2.1 of the appendices for evaporation.

Table 10.1 Long-term monthly rainfall in the KBV sub-catchment, expressed as a percentage of MAP.

Month	**Oct**	**Nov**	**Dec**	**Jan**	**Feb**	**Mar**	**Apr**	**May**	**Jun**	**Jul**	**Aug**	**Sep**
% Rain	6.87	4.55	3.06	2.07	2.62	3.60	7.32	13.62	16.74	15.75	14.37	9.48

10.2.2 Aspoort historical simulation

The existing Aspoort scheme covers a comparatively small area where the full extent of the catchment and its hydrology are considered. The simulation showed that in the past, there was no period when water supplies were below 80 % of the demand, and this never occurred more frequently than once in five years in the Doring River for the Aspoort Irrigation scheme. The monthly water demand and supply are shown in Figure 10.5, where water supply levels are approximately the same as the water demand. Simulation of the present state of the Aspoort irrigation scheme, based on historical records, showed that, if the present state of water storage in farm dams and irrigation development existed through out the past 75 years, then the water demand would have been completely satisfied for the entire period. Table 9.4 of Section 9 shows the historical trend of the state of dams and irrigation development in the catchment.

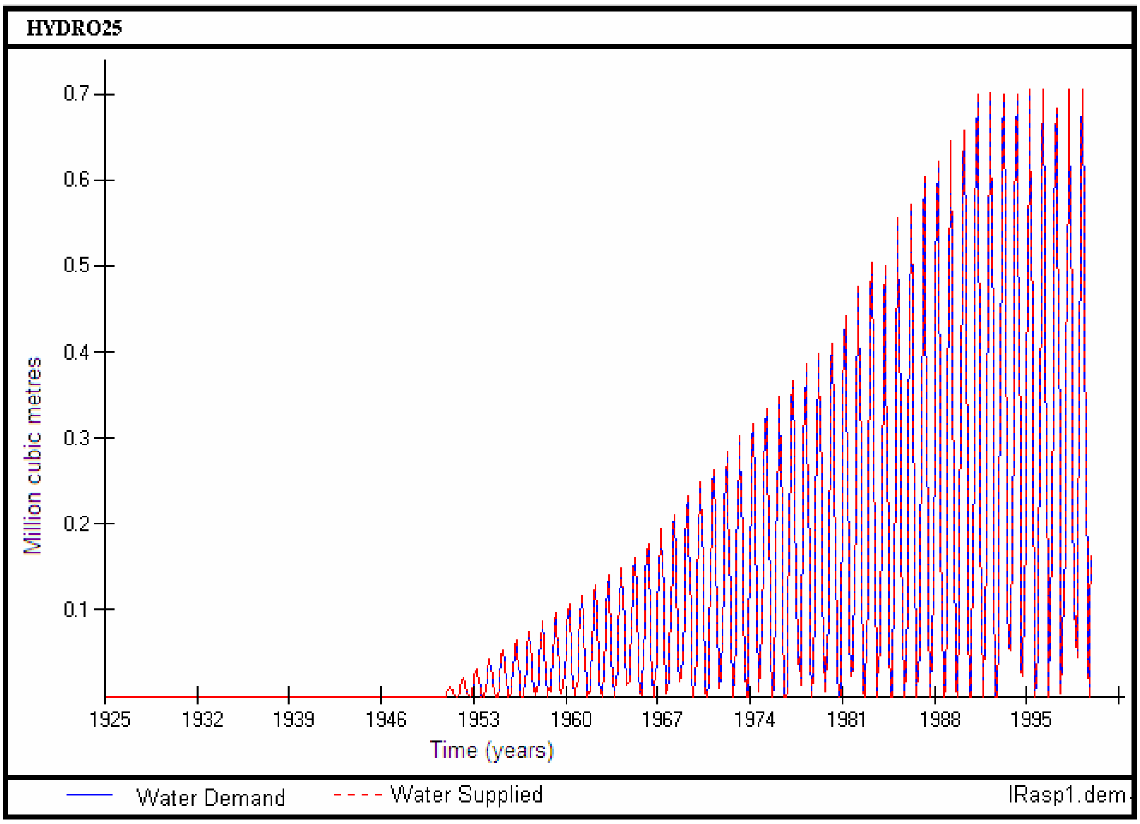

Figure 10.5 Growth in irrigation water demand and supply for monthly time steps in the Aspoort scheme, based on catchment development over the period 1925 to 1999.

10.3 Koue Bokkeveld irrigation development assessment without additional storage

Simulation of the proposed development at the KBV catchment involved applying different fixed areas of irrigated land over the entire simulation period, while maintaining the same 1999 storage development level. A number of simulations were done with changes to the area of irrigated land only. The 75-year historical hydrology was assumed to be the closest available reflection of the catchment hydrology for the 75-year projection of irrigation development proposals. In the simulation, the irrigation of more than 700 ha in the proposed Aspoort scheme without additional storage generated a risk level higher than the 1 in 5 year irrigation failure level that is used in DWAF's Planning Directorate. A failure occurrence was defined as a year when water supplies were below the 20 % satisfaction level, that is cases when less than 80 % of the water demanded was supplied. Figure 10.6 shows the annual irrigation water demand due to the additional 700 ha irrigation scheme in the KBV area, as well as the water supplied to meet the demand. Calculations using the simulation results illustrated in Figure 10.6 showed that, out of the 75-years simulated, 12 years had water supplies that gave a demand satisfaction level below 20 %. The irrigation of 700 ha with a risk level of 16 % was considered to be the maximum development possible without including additional storage in the catchment. Increases in the area of irrigated land to more than 700 ha gave poor satisfaction levels. The poor satisfaction in irrigation demand in this case refers to a situation where water demand is not met for at least 20% of the period considered (that is a situation where incidences of failure to adequately meet irrigation demand occur more than 1 in 5 years).

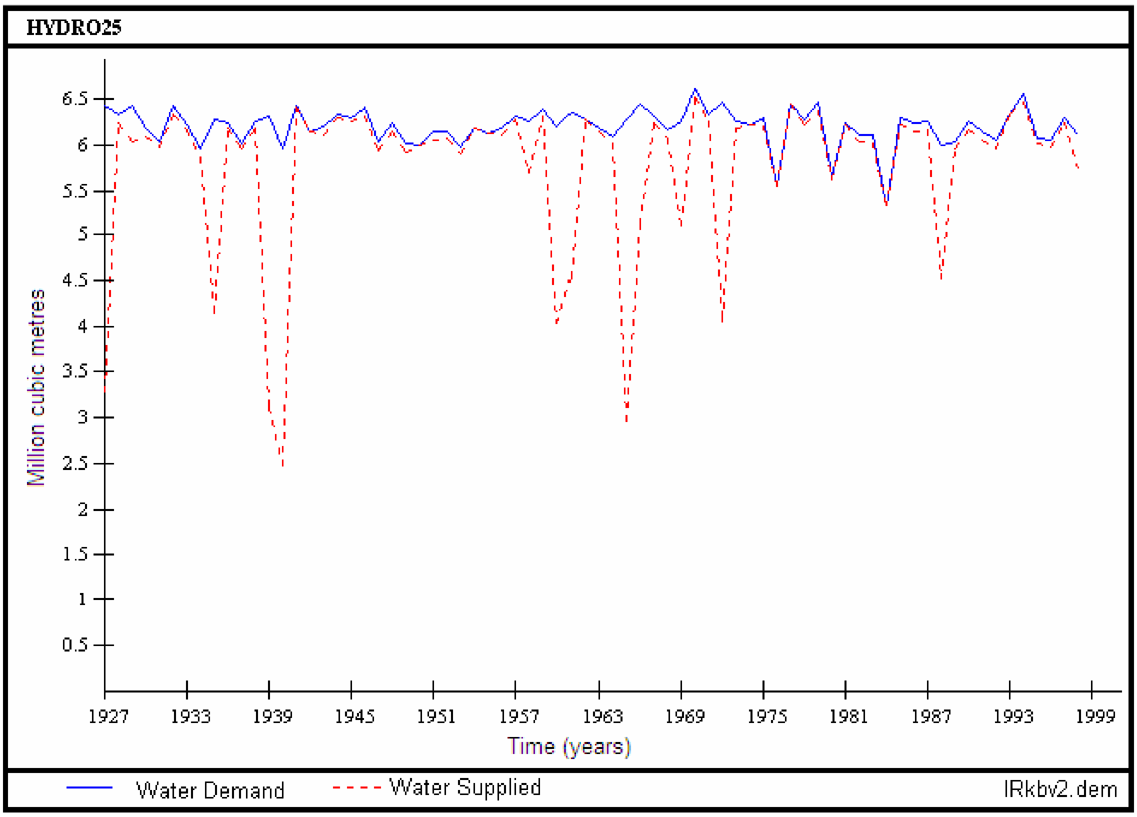

Figure 10.6 Annual irrigation water demand and supply results for the proposed 700 ha irrigation in KBV.

10.4 Aspoort irrigation potential with the proposed additional water supply reservoir

The simulation of development proposals at Aspoort involved inclusion of the proposed Aspoort Dam with a storage capacity of 178 million m^3. The scheme failed in the simulation as shown by the extensive water shortages that occurred when the historical records were used. Figure 10.7 shows the level of annual water supplies and the irrigation demand, while Figure 10.8 shows the extent of the water supplied as a percentage of the water demand (*i.e.* the irrigation demand satisfaction level). Out of the 75 years simulated, water available to meet the demand was below the 80 % satisfaction level for 42 % of the time. This result gave a risk level of failure of once in two and half years, assuming that future trends in the catchment hydrology will be similar to those that have been observed over the past 75 years.

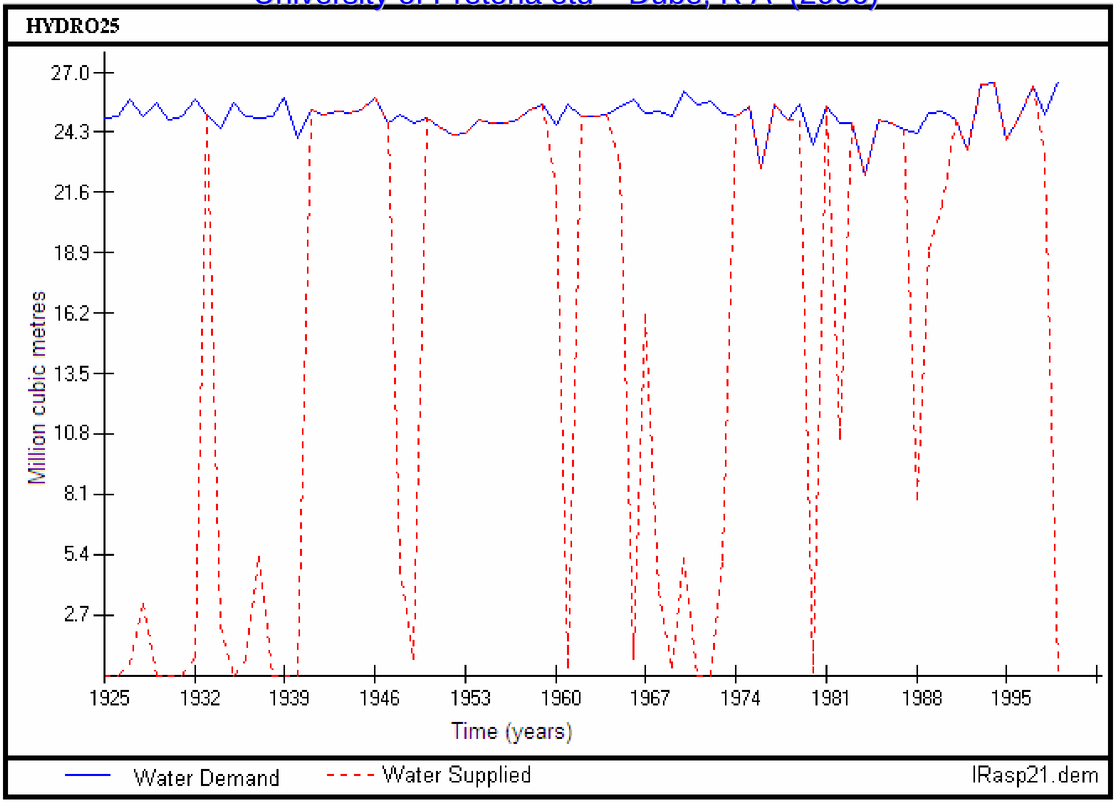

Figure 10.7 Irrigation water demand and supply for the proposed 3000 ha development option at Aspoort.

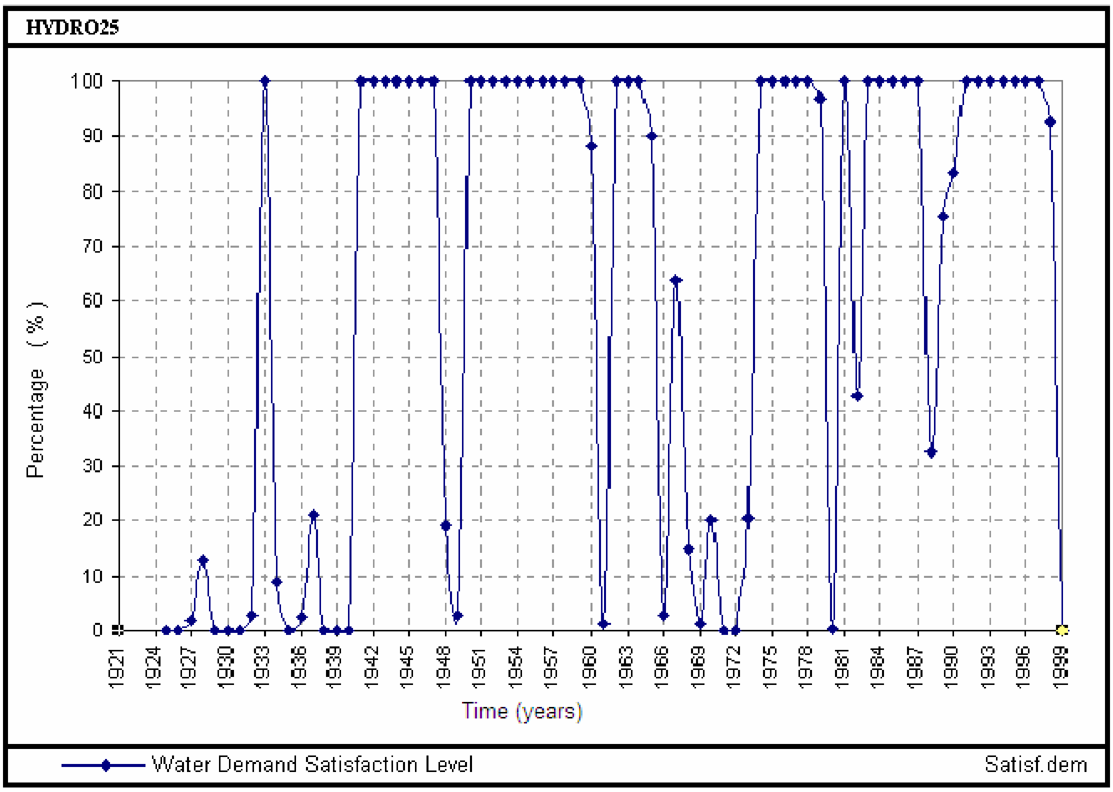

Figure 10.8 Irrigation water supply as a percentage of annual water demand for the 3000 ha development option at Aspoort.

Further simulations of the Aspoort irrigation scheme revealed that the scheme will only be able to achieve an acceptable 20 % risk level if a maximum of 1000 ha is irrigated. The results in the Figure 10.9 show the level of water demand and failures for the irrigation scheme when 1000 ha is under irrigation.

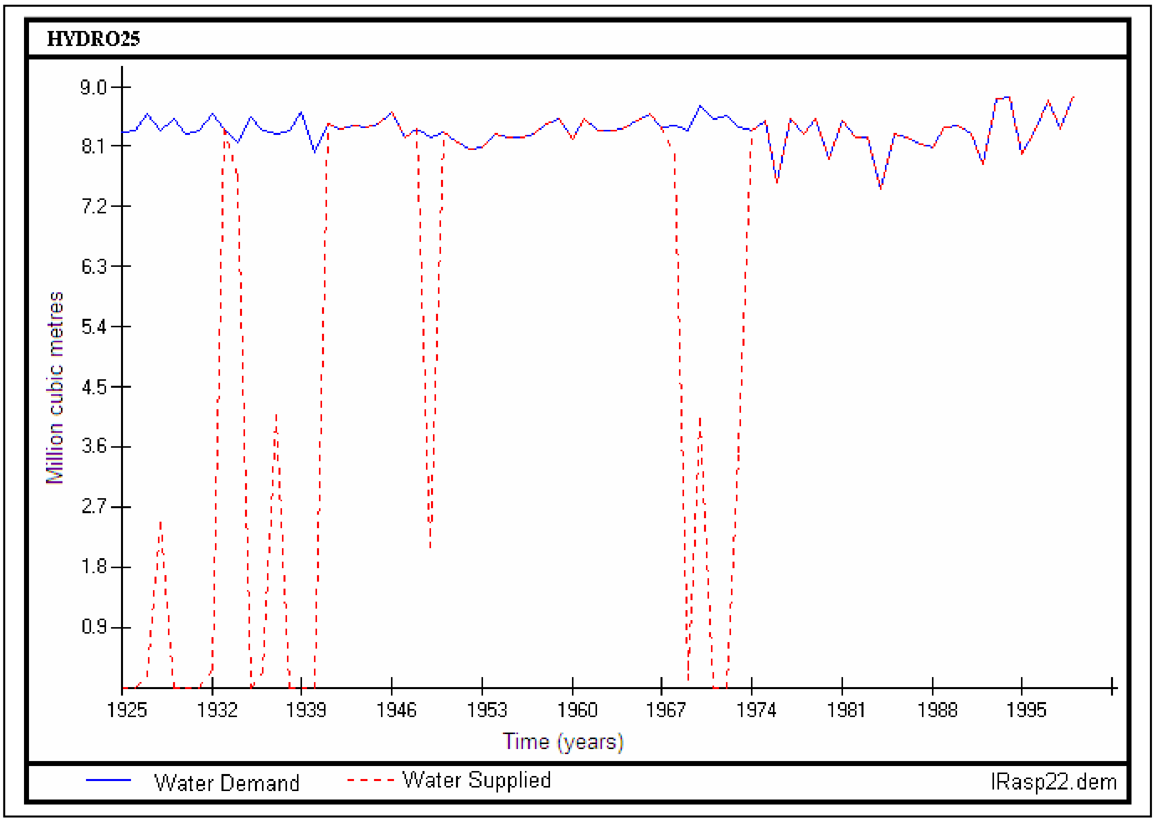

Figure 10.9 Irrigation water demand and supply for the proposed 1000 ha development option at Aspoort.

Chapter 11

Conclusions

11.1 South Africa's unique challenges in surface water resources modelling

In South Africa, most of the available water resources models were developed overseas, especially in Europe, North America and parts of Asia. These imported models are usually not directly applicable in South African regions which have a number of unique regional climatic and physical characteristics that affect the model performance. Model developers, or those tasked to procure water resources models, should be aware of the unique characteristics in our environment that affect model outputs. The key variables amongst South Africa's unique variables and the ways in which they affect the modelling process were identified in this study and are discussed as follows:

- The seasonal climate variations and weather patterns in South Africa are unique to this region. South Africa is considered to be mostly subtropical in the North, which changes gradually to a temperate and to some extent Mediterranean climate in the south of the country. Most imported models were developed for use in wet, temperate climates, with defined cold and icy weather conditions. In contrast, South Africa is characterised by mostly dry and hot sub-tropical areas where national rainfall averages 462 mm and where 91 % of this rainfall is lost to evaporation. Most models developed for the temperate climate of Europe and parts of America are not readily applicable to South Africa due to major climate and weather differences. Local modifications of these models to suit conditions in South Africa are usually restricted by the absence of rights or licenses to allow access to the software code. The costs of obtaining appropriate licences are so high that they are a further barrier to model access. In some cases, free software with limited functionality is provided to the user as a way of marketing the full package. This approach is even more detrimental to water resources management and planning as users usually end up using these incomplete and inappropriate packages to solve problems of national importance.

- South Africa is characterised by highly variable water demand distribution, with a few urban areas demanding more water than is available in their catchment areas. As a result, water distribution in South Africa is characterised by an extensive network of water transfers from more distant catchments where sufficient water is available. Water resources modelling should be able to integrate the various components of the water system, throughout the regions of influence, without being restricted by the catchment, or by administrative, political and other boundaries.

- Variable water demand patterns resulting from population redistribution as people migrate to urban settlements, as well as the impact of the deadly HIV/AIDS pandemic on the population growth rates and people's life expectancy, mean that water resources modelling tools have to account for the causes, implications and results of a largely unstable and unpredictable population demography.

- South Africa has limited data and few resources are available for developing additional data source points such as additional weather stations and flow gauging weirs. The water resources models used and developed must fit within the boundaries of available data. Promises and expectations of data improvements should be investigated and verified before one develops a model that seeks to utilise data that will be available in the future. In the case of rainfall gauges, Lynch (2003)'s investigations revealed that the few new gauges that are being developed are only replacing closed gauges rather than improving the distribution of data sources. RADAR and satellite data, which give the usually preferred aerial data as opposed to point data, are hardly useful on their own in models that are based on time-series data. Some of the limitations with RADAR data are that the local records are usually shorter than ten years and still have to be corrected using field measurements. On the other hand, satellites, another important alternative source of data, provide data that are not continuous; for example Landsat-7 provides data for an area once every 21 days.

- The South African water resources modelling industry and market is small. Due to the limited market size, few developments and enhancements to water resources models occur. These model modifications usually involve minimal redevelopments of existing software to give the model a face-lift as well as address some basic stakeholder expectations in the model. Existing models and model development processes in South Africa have therefore gone through little evolution, when compared to other highly competitive markets with numerous users and developers such as in the United States of America and Europe. Dent (2000) sums it all by saying that the South African water resources modelling industry is still in the pre-DOS era. Ideally, new model developments should target local use as well as use outside of South Africa, especially in other African countries with similar water resource issues and comparable natural conditions such as the climate, vegetation, weather and soils. These developments should aim to take advantage of the international technology transfer vehicles that are being established through international initiatives such as the New Partnership for Africa's Development (NEPAD). The international water resources model market is large and provides a range of feedback from a variety of stakeholders who have different experiences. This provides the required dynamic platform for the development of dependable, widely tested and accepted models.

- South Africa is faced with new issues in water resources as a result of its new legal framework. The NWA's principles of equity, efficiency, equality, sustainability and economic benefit, meant that many of the rules used in existing water resources management and planning models have to be changed. In some cases, the introduction of new model rules is required to ensure legal compliance in water resources management and planning. On the other hand, the NWA also introduced new water use definitions and revised the criteria for water use licensing. These legal requirements in the NWA have to be part of the models to be used. The delegation of DWAF's planning and management functions to CMAs mean that water resources modelling at smaller spatial and temporal scales is now preferred to handle the needs of WMAs. Since most of the existing tools deal with water resources at large scales such as quaternary and monthly time steps, they will still be useful for national water management. Smaller scales in water resources modelling mean that more data are required, as well as the need for higher resolution supporting tools such as DEMs, GIS and Structured Databases.

- Most of the available modelling tools in South Africa were developed well before the development of the internet for public use. Rapid recent IT developments, including the Internet, have emphasised the need for reengineering and redevelopment of out-dated water resources modelling tools. These model revisions are expected to utilise the improved IT functionalities to generate models that are more accessible to users, models that have a comprehensive user support system, including manuals, help facilities, error handling support software, and are easier to integrate with existing software.

- Software developers of the past including those who developed all the important South African models, depended on the principle that code secrecy was their recipe for business success. Today, software that is not open-source is shunned by many users and fails to reap the benefits of wide community involvement and feedback. In some cases a very limited group of users know how to use a particular model because there are no manuals and the knowledge is passed down through practice rather than other forms of training and model related publications. This has had a detrimental effect on prospects for further model development and has also drastically limited the model user base.

- There are no established codes of practice or guidelines in water resources model development and use. A national advisory committee to guide and direct the process of model selection and use for DWAF water resources projects is still to be set up. Establishment of guidance systems to the water resources modelling practice will help to ensure that modelling practice is maintained at high levels of quality, cost-effectively. However, there is a risk that platforms set to guide and direct modelling may end up giving an unfair advantage to selected models, and creating an environment that lacks competition and creativity.

11.2 Planning and the use of models in the water resources sector

Section 2 of this study revealed that the planning process for water resources development involves a number of factors which include: determining the most influential points in the decision making process, defining the goals to be met in these areas and then setting a hierarchy of priorities to meet those goals. While there are several definitions of water resources planning in current use, they share the same principles which are: (1) the scope of the water resources problem, (2) the level at which the problem will be handled, and (3) the resources available to analyse the problem and develop solutions.

Evaluations of viability of water management systems and water projects based on hydrology, depends on many parameters that require multi variable modelling tools, such as HYDRO25, to provide information that will be used by decision-makers. Water resources managers should always bear in mind that the hydrological feasibility of a particular action or choice that is assessed using hydrology-based tools such as HYDRO25, is not the whole story in water resources planning. Other equally complicated assessments such as economic, environmental, social and institutional viability must be considered at different stages of project assessments. The planning process in water resources management has to be carried out as a multi-criteria process that accounts for all the variables involved. The process to generate information on the different issues (hydrology, environmental, economic, sociological, political, e.t.c) can take place in different compartments that are linked or integrated to the other compartments. The outputs from these information generation compartments will finally be integrated to feed into the decision making process.

Ideally, planning for the utilisation of water resources in South Africa should take account of all the information related to hydrological processes in each catchment, and the interactions between hydrological and other non-hydrological processes. The goal of deriving solutions that approximate an ideal water systems state has meant that catchments should ideally be simulated in ways that relate very closely to the physical state of the catchment. Such physical models are challenged by the absence of adequate time series data. A balance of a conceptual and physical approach produces a more practical approach in South Africa.

A number of water resources models have been developed for different reasons, including their use as "once-off tools" applied in a single study. Others have been developed as generic models for application in a number of studies, while yet other models were developed for use in academic environments as teaching aids that are used to illustrate hydrological processes to students. Out of these models, many have failed to be accepted as useful modelling tools by different institutions, because of the reasons that are discussed in the following paragraphs. Examples of widely accepted modelling tools in South Africa are the WRSM2000, WRYM and WRPM models. These models have been used as standard tools by DWAF for the development and operational planning of water resources in South Africa's major catchments since the commissioning of the Vaal River System Analysis Study in 1986 (BKS, 1986; Van Vuuren *et al.*, 2001).

A model is usually not accepted by stakeholders immediately, but goes through a rigorous process of technical and social evaluation. Only once the model has been evaluated by prospective model users, and the developers have made improvements and enhancements based on the findings of evaluators, can such a model become an acceptable and useful tool in the water industry. In some cases, it takes a long time for stakeholders to be satisfied that a particular model meets their needs; an example is the ACRU model where DWAF have always maintained some doubt on the applicability of the model in large catchments required for national planning. In a bid to improve model acceptance, DWAF funded a project to evaluate the applicability of the ACRU model in large catchments (Mathews and Langout, 2001). Mathews and Langout (2001) found that the driver rainfall station approach in the ACRU model, that was developed for use in catchments smaller or equal to 25 km^2 (Seed, Schulze, Dent, Lynch and Schafer, 1995) was a major setback when one simulates a typical South African catchment that has sparsely distributed rainfall stations. With a total land area of above 1.22 million km^2 and less than 3000 active rainfall stations (Lynch, 2003), South Africa has an average rainfall station distribution of one station per 400 km^2 of land area. Water resources managers should bear in mind that, while it may take long for a model to go through cycles of evaluation and further development, slight changes in other variables such as the legislation will easily affect the model applicability and acceptability.

In this study a number of reasons have been noted as underlying the failure of some models to be accepted as routine tools in the water sector. The following are some of the main qualities that were identified as the most important characteristics of a surface water resources model that is likely to receive nation wide acceptance:

- The model has to be developed with a strong local background to be able to include all the basic expectations, requirements, standards and climatic conditions of the environment in which it will be used. For example, the South African objectives of satisfying "reserve" water requirements before other water uses; the nature of the climate in South Africa; and the knowledge of the community that will use the model; are all important factors that must be incorporated into the model development process. A well-informed local water manager will not easily identify with a model that was developed and tested in another environment that he/she has little knowledge of. In many cases, the test area will have little resemblance to the situation that he/she wishes to model. A process of model evaluation, redevelopment and testing in the targeted area of use should be incorporated as part of any project that intends to use models developed in a different environment.
- The model has to perform to expectations. Inaccurate results from a model give the model poor credibility and repel potential model users.
- Model development has to involve decision makers, water managers and model users in the water resources sector so as to allow for inclusion of current important trends, such as water reserve objectives in South Africa, and to allow a wider evaluation of the model development process to improve the model's position in the water industry.
- The modelling process must identify with the "local" objectives and the processes involved in the planning of water resources. Thus, model development must take place with the water planner in mind, whilst his/her institution and the framework in which it operates should also play a central role.

11.3 The model development process

One of the key aspects of good model development that were identified in the development of HYDRO25 was the need for wide participation of water managers and water resources decision makers. While early work in this model did not adequately involve stakeholders it became apparent that good model development is a result of adequate inputs from the scientific stakeholders, water sector leaders, decision makers, model users as well as the lay public. Improvements in user acceptability as well as model conceptualisation could have been achieved if the model development had been based on a solid foundation of stakeholder consultations. Other conclusions that have been derived from the model development process in this study include the following:

- Model development in the water resources sector should not be a function of software developers who have little knowledge of the science behind the model formulations, namely water resources engineering and hydrology. The most important aspect of a good model is not the software, but rather the applicability of the concepts and equations contained in the model.
- A model is a useful tool only if it provides better information to the decision-maker than could be obtained without the model. The model has to be built within the paradigms of the information technology "norms" prevailing at the time. As a tool, the model should not require the procurement of a new computer or installation of new software, and any additional expertise needed should be minimal.
- The development of the model HYDRO25 showed the importance of building a model around locally tested and accepted ideas that range from the use of the Pitman rainfall-runoff equations for South African users (Pitman, 1973), to the use of familiar MS Windows objects. This software development aimed to retain a "look and feel" that has been established by commonly-used software packages such as the Microsoft Office applications.
- A water resources model has to be developed with a sound understanding of the best ways to handle data in the most readily available formats. The use of data formats such as the HRU format for monthly data, and the ACRU model single format for daily data in HYDRO25, was one step towards development of a model that has a

strong link to the data environment in which it is expected to operate and existing local knowledge.

- The development of the user interfaces in the HYDRO25 model and the associated visual options brought to the forefront the idea of making sure that the model represented the catchment as accurately as possible. The model user requires to visualise what is happening in the model and the modelling experience must not be difficult to comprehend. HYDRO25 took advantage of continuous improvements in computer hardware and operating systems, where increased processing speed and memory capacity and improved handling of graphics, allow greater representatively and deeper perspectives to be achieved. These improvements in the computer sector have meant that water resources models can enhance the visual and interaction advantages for model users, giving the software user an experience that is related to the mental picture he/she creates of the physical catchment.
- The use of Microsoft Windows objects in HYDRO25 made this model easy to maintain and run in the same environment as most other Windows applications that are used by the majority of the water sector stakeholders in South Africa.
- A model developed for use by water stakeholders who are dispersed in time and space must be easy to deploy in a way that allows each user to access and run the model at his own pace in his own environment. To achieve this situation with HYDRO25, the model was developed so that it could be fully functional from a compact disc or from any other single magnetic storage facility, without the user having to install it onto another system, a process that was noted in the early stages of model development to cause complications and user resistance.
- The development of HYDRO25 took place in the environment of its use, with the data for simulation at each point available in a form that allowed model verification to be part of the development process. Model development should not take place in an environment that is isolated from the environment of its use.

11.4 Doring River system case study

The following conclusions were drawn from the simulation of the Doring River system using the HYDRO25 model:

- The poor availability of high quality data, especially for rainfall and runoff, proved to be a major obstacle in ensuring a smooth study process for the Doring River catchment. The data were found to be scattered in the water industry, with a number of organisations having their own sets of data that they had collected and stored and, in some cases, processed without a central data co-ordination system. In many cases, this resulted in different organisations recording different values for rainfall gauges with the same name. The collection, storage, and processing of hydrological data was identified as an area that required more attention in the water sector. A possible solution to such data-related problems would be to develop a national organisation or company that could take responsibility for collecting, processing, storing and distributing all data required in the earth sciences. The absence of a good national (*i.e.* centralised) system of data storage and maintenance is a lost opportunity. Having such a facility could reduce national expenditure on data management. In the water sector, a lot of time and money are spent compiling data and other resources to use in water resources management studies. The costs incurred are usually borne by the clients in the form of overheads and, in some cases, as direct costs which have to be dealt with as separate projects with their own budgets. In many cases, subsequent studies also go through the same process of compiling and processing the same data and, then charge the client again for their efforts, when the earlier results could have been stored in a centralised system and simply made available to every subsequent investigation.

- With a catchment MAP of 553 mm and an average crop water requirement of more than twice the MAP (Green, 1985), the success of agriculture in the Doring River catchment relies on water being supplied by irrigation schemes. Higher rainfall (up to 700 mm/yr) is concentrated in the steeper mountainous parts of the Doring River catchment, while the flatter lower lying lands with lower rainfall (269 mm) have the best irrigation potential in the catchment. These factors mean that suitable water storage facilities are needed, as well as a carefully planned system of irrigation schemes in the lower reaches of the catchment. The Aspoort and the KBV schemes that were assessed in this study were found to have good potential for further expansion.

- In the calibration of the Doring River system model, the level of hydrological data inputs available became the major factor in deciding on how to lump and simulate the catchment. A detailed catchment representation with very small sub-catchments connected together is the ideal state in catchment modelling. This case study showed that there is an acute need for more numerous rainfall gauges, runoff gauges and evaporation measurement stations in the catchment, if better representation of the catchment is to be achieved. The focus on upgrading all aspects of data recording should start with the revival of several gauges that have been closed in the catchment. The current average distribution of rainfall stations in South Africa is one station per 400 km^2 of land area.

- The available tools and the knowledge possessed by practitioners in the water sector has a major bearing on what can be done to provide decision-makers with the best possible information. Cases were encountered in the study where data were obtained from some sources in haphazard formats that included image type formats. Such data can be referred to as being "available", but they are not useful to a water resources planner using modelling to obtain information. In this study, it was felt that decision-makers in the water sector have to have a thorough understanding of the issues they are working with and how their objectives are likely to be met.

- The simulation of the Doring River system showed that if hydrological parameters alone are considered, the irrigation development could be larger than 750 ha in the KBV area without the need for additional water storage. In the Aspoort irrigation scheme, a maximum of 1000 ha can be developed in conjunction with the KBV scheme. A storage impoundment with a capacity of 178 million m^3 would need to be developed to meet the water demand in the Aspoort irrigation scheme.

Chapter 12

Recommendations

12.1 Modelling as a tool in planning

The planning of water resources should be based on the best available information for all the criteria that are determined to be important for decision making. The development and upgrading of water resources tools have to be continuous processes that take place in a competitive environment where innovation thrives. The major stakeholders in the water resources planning sector, that is the national water department, catchment management agencies, water supply utilities and municipalities should take firm steps to build a competent water resources planning environment where specialists with a variety of different ideas can contribute to the information provision process. It was noted in this study that there is a general reluctance and a lack of adequate support to develop and update modelling solutions from the previous decade as well as from the more distant past. Most developments to existing models are superficial, focussing on minor revisions such as improvements to user interfaces. Water resources planning decision-makers should welcome new techniques on water resources planning issues and work towards meaningful upgrades to existing models and building other new water resources planning tools. This is expected to create a vibrant planning environment that is conducive to the generation of sustainable, high-quality water resources solutions. Computer applications that fail to fulfil basic user requirements, demands, desires, and hopes in a user's attempts to reach a goal, are a source of work-related stress.

In South Africa, those water resources that are easiest to extract and utilise have already been exhausted, as can be seen by the growing need to utilise ever more complicated water transfer systems. This has meant that bulk water supplies today require decisions to be made on strategies that were never considered in the past; a situation that has also been described by Ohlsson (1995). There is a growing need to design and implement optimal solutions to achieve cost savings and allow water stakeholders to address other important issues without having to spend excessive resources working on one possible solution that may never be implemented. Suggestions to use more comprehensive water management tools that use the most up-to-date techniques that have been tested and successfully applied, such as genetic algorithms in water sector planning, need serious consideration and support.

The search for optimal solutions in planning should include all known possible scenarios that could affect the results of the planning process. Many catchment studies involving operational assessments, water yield evaluations and the planning of new infrastructure are repeated, or in some cases tackled from a number of approaches at different times, by different consultants, because the criteria used to evaluate solutions are incomplete. In some cases, these incomplete solutions date back to the time the project was first proposed.

Water resources projects have to be carried out within the boundaries of the prevailing water policies. The normal practice in water resources management in South Africa has always placed more emphasis on addressing water availability in terms of quantity and within the specified time frames, and has usually failed to adequately address water quality issues and equity in access to water. These limited scope studies with non-comprehensive approaches are very likely to have to be repeated in the near future. Pape (2001) pointed out that the equity shortcomings of the Hermanus Water Conservation Project contributed to what was widely reported as a success story of this project, with recommendations for other municipal authorities to follow. Pape (2001) suggested that there was an urgent need for the Hermanus Municipality to implement another project to holistically address the shortcomings of the original Hermanus Water Conservation Project. The water stakeholders, especially the decision-makers, must be well-informed about all the variables associated with particular water problems and solution developers should ensure that water resources projects or programmes are holistic rather than being narrowly focused, requiring immediate upgrading or repeating.

Water resources modelling tools should not be developed or used to create further complications in planning. In water resources planning, stakeholders usually seek tools that enhance their problem conceptualisation and improve the processes of solution development, which in most cases involves the analysis of many variables. A significant number of South African tools, including the National Water Resources Planning and Water Resources Yield models have been noted to be of such complexity that their use is restricted to a few individuals (Hughes *et al*, 2004).

12.2 Development of water resources models

The development of water resources models in general should be in harmony with the existing water environment variables to provide a good representation of the prevailing physical water system characteristics. Without model development guidelines or some form of agreed modelling procedures, model developers are likely to produce models that fail to meet all the goals and the standards set in the water sector. The guidance on the model development and use is expected to help to ensure that water solutions produced have the national interest at heart, since water resources are of national importance. Based on the results of the study, it is recommended that the considerations made in the development of a water resource model must include the following:

- Available data in terms of spatial distribution, record length and completeness
- Data quality in accuracy, continuity, representativeness and readiness for use
- Policies and legal tools such as the water management policies and water Acts
- Climatic and weather factors
- Soils, vegetation and topography
- Land use and human settlement patterns
- Water institutions and how they position modelling tools in their processes
- Political and trans-boundary issues
- Prevailing information technology environment and available software
- Social and economic issues including the social welfare aspects of water resources
- National and world wide trends in water resources management and planning

A case study in the development of the model HYDRO25 in this study revealed key issues that need consideration on the software aspects of the modelling process. The development of water resources models should aim to produce software that:

- *Is user friendly,* with menus, dialogue boxes, icons, and context-sensitive on-line help to shorten the learning curve and guide users through the catchment model set-up, model execution and interpretation, without having to consult the users' manual frequently. Error handling techniques must be comprehensive to allow the model user to identify all points of errors and understand why these errors occurred. Model users should not be required to memorise the command syntax. This can be achieved by replacing text commands with interactive graphics that have visual clues on what will happen when the user interacts with them. The model development must avoid the use of traditional ASCII output files, and use graphs, charts, and plots which can be easily and quickly understood by the users.
- *Has automated file management:* Water resources models usually generate large numbers of intermediate files that are shared among various model modules. Manual management of these files is cumbersome and prone to errors. Automatic organisation, connectivity and formatting of these files should be provided within the model.
- *Has seamless integration:* Various modules should be seamlessly integrated in one program that eliminates sequential batch processing of modules. Users should be able to perform various tasks (*e.g.* input, editing, execution, plotting, *etc*.) from within one program rather than having to run multiple programs to do various tasks.
- *Provides accurate, repeatable and reliable outputs:* Decisions made on water resources have direct implications on many issues which include very important initiatives in national planning and global sustainability such as the programmes on the Millennium Development Goals (MDGs). It is important that these water resources decisions are made using the most accurate and reliable inputs.
- *Is understandable and logical because it reflects reality:* Model users and decision makers are naturally inclined to understand tools that logically relate to or mimic the physical characteristics of the water resources problems that they wish to resolve.
- *Is not over-simplified:* The water system, user requirements, needs and desires, legal water environment, socio-economic factors and other water resources variables present complex relationships and characteristics in water resources decision making which cannot be easily resolved through over-simplified tools such as the use of rules of thumb. Sufficiently holistic multivariable tools based on a sound scientific basis usually present the best solutions for water resources problems.

12.3 HYDRO25, further development and use

In the case study of model development, the rainfall-runoff simulation routines of HYDRO25 require further improvements, especially for use in cases where the model has to simulate catchments that are smaller than the Doring River study, as discussed in Chapter 9 and Appendix A2 of this report. In small catchments, more accurate accounting of water in the system will be needed than that achieved with the Doring River catchment. The extent of the errors generated in the simulation of the Doring River to meet set objectives, especially the standard deviations and flows in years of low rainfall, meant that catchments smaller than 100 ha are likely to give results that are inadequate for the types of assessment that was carried out for the Doring River.

The use of graphical interfaces in modelling and the use of geographical information systems to display and analyse the spatial nature of water resources systems is seen as critically important feature of all current and future water resources modelling. The HYDMAP interface in HYDRO25, which is currently used to display outputs and edit inputs, has the potential to facilitate the redevelopment of HYDRO25 so that all model input data are completely connected to catchment maps and aerial pictures. Integration of the model with catchment maps, pictures and code routines to allow connectivity in the manipulation of maps and numeric data, will give the model a geographical base that will help to improve understanding of the modelling process, the catchments simulated and the information generated.

The testing of the model HYDRO25 in other catchments outside of the Doring River system is recommended before the model is made available for wider use by other practitioners. The use of the model in any catchment will require a new network definition; this can be achieved through entering the inputs for the modules selected by the user to represent different processes in the catchment. New inputs for the catchment will include: monthly recorded rainfall, daily recorded rainfall with a record length of at least one year, monthly runoff records of not less than ten years, long-term average of monthly A-pan and Symon's pan evaporation data, catchment area and water use data over the period covered by the hydrological records, and rainfall-runoff parameters as the major inputs. Model calibration using accurate catchment runoff records with a length of at least ten years will be required for the rainfall runoff routines. The development of HYDRO25 was aimed at developing a generic model where the code routines incorporated equations and processes that use parameters and data inputs that were not restricted to one catchment. The evidence provided in this study indicates that the original objectives for the development and testing of the HYDRO25 model as set out in Chapter 8 were met successfully.

12.4 Towards a preferred water resources modelling scenario in South Africa

The water sector in South Africa was developed many years after key developments were made in many countries especially in Asia and Europe. As a result, many water resources management and planning initiatives were imported or were a result of upgrades on foreign developments. Increasing globalisation, wider sharing of ideas, new technologies and other resources are now key factors in any sector including water resources. South Africa, however, has other unique characteristics where local initiatives are expected to generate solutions. Practitioners in the water sector have to ensure that all of the solutions that are imported or developed are suitably equipped to address the unique South African characteristics. These unique characteristics include the following:

- A unique Water Act (Republic of South Africa, 1998): In addressing the requirements of the Water Act, water resource practitioners and decision makers should realise and work in harmony with the extended pressure resulting from the political transformation process. However, solutions developed should not end up giving undue focus on political needs without adequately accounting for other factors such as establishing a sound scientific base.

- The state of our data resources. Our data resources, especially time series data, are generally more sparsely distributed, usually discontinuous and are seldom ready for use when compared to the data resources in countries where most of the available water resources management and planning tools and techniques originate. Appropriate techniques to improve data resources, such as the development and use of stochastic data generators, should be pursued while programmes to develop permanent and adequate data collection, processing and archiving structures are being put in place.

- The capacity of human expertise and technology in water resources planning and management is very limited, when compared to the country's needs. The few researchers and other technical teams that are involved in water resources management and planning do not have the correct mixes of suitably qualified experts. As a result, the range of recommended tools as well as technical developments are limited to the available skills base.

The South African national policy and guidance on software use and development are still to be developed and applied. One recent key technological decision was the decision by the Government, a key stakeholder in water resources management and planning, to take the open source software route. Stakeholders in the water resources sector are expected to evaluate their software decisions in light of key Government recommendations such as recent developments towards the use of open source software.

It is also recommended that all levels of stakeholders as defined in section 3.2.2 should be part of national initiatives on the development and procurement of water resources tools. The WMA based approach in the NWA allows such general involvement at different levels. Decisions on the use of key modelling components, such as GIS or other imported tools where local replacements are not available, have continued to suffer from the conflicting recommendations made by stakeholders who are usually poorly equipped to provide competent decisions that take into account all the variables involved. This calls for empowerment of all those involved in decision making through education and training. This study confirms that the planning and management of water resources is to a large extent a national duty. As a result, this study recommends that decision makers, for example the soon to be formed "Minister's advisory committee on water resources modelling", should be empowered and equipped with resources to identify, seek and facilitate the development and use of suitable modelling tools that are economically beneficial to the nation.

- The level and distribution of expertise in water resources management and planning teams is usually limited. These teams of water experts should widen their core groups to include different stakeholders in different disciplines, different user groups as well as the same disciplines with different approaches, such as daily hydrological modellers and monthly modellers in hydrology.

Practitioners and experts in the water sector should realise the need for holistic approaches and ensure that their teams are well balanced in terms of scientific or discipline groupings, as opposed to the prevailing trends which tend to promote the existence of "silos" in stakeholders groups. Theses "silos" produce narrowly focused solutions with limited applicability.

This study also confirmed that individual water resources model developments are usually poorer in focus and seldom holistic; as such, these should therefore be avoided. Existing water resources tools have to change from their present predominantly single subsystem, sectoral and sectional approaches, to become holistic and integrated.