Appropriate positioning of modelling as a decision support tool for surface water resources planning in South Africa

by

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DECLARATION

I declare that the thesis, which I hereby submit for the degree of Philosophae Doctor at the University of Pretoria is a result of my own work and has not been submitted previously by me for a degree at another university.

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APPROPRIATE POSITIONING OF MODELLING AS A DECISION SUPPORT TOOL FOR SURFACE WATER RESOURCES PLANNING IN SOUTH AFRICA

BY

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Summary

The availability of adequate information is one of the basic requirements of sound water resources development. Simple water resource development options that required less detailed studies have already been developed, such that development proposals today require more detailed and comprehensive studies. Among other factors, these studies generate information on the hydrological risk of implementing water resources projects. The modelling tools used to generate water resources information are usually complicated by the many variables involved, which are inter-linked and usually unpredictable. The National Water Act (Republic of South Africa, 1998) emphasises the need for integrated water resources management, social equity, and ecological sustainability, which have added new dimensions to water resources planning. Water catchment simulation models that account for all the dimensions of water resources planning and bring more information than ever before to the decision-maker have become the preferred tools.

Whilst earlier water resources planning tools are still in common use, this study found that these earlier tools lagged behind developments in important aspects such as national legislation, water stakeholders' working environment, and rapid changes in computer software and hardware. The appropriateness of water resources modelling tools in South Africa was investigated in the light of a changing water environment as well as the need to address specific factors that are unique to South Africa. The water resources factors investigated included hydro-climatic, water institutional frameworks and stakeholder needs, available expertise and technological aspects of the available water management and planning tools. On the basis of the outcome of the investigation of South Africa's unique water environment, recommendations and guidance were developed with the aim of developing a preferred local water resources modelling approach.

This study investigated and recommended the use of water resources system models which are based on up to date modelling and Information Technology (IT) developments, such as HYDRO25, for multi-criteria planning of integrated water resources. In this study, the development of object oriented programming (OOP) models with visual interfaces that fit in the popular Windows operating environment was distinguished as a key aspect of water resources modelling. This modelling route was selected because it generates tools that are more user-friendly, have visual clues that relate closely with the physical system, including easy GIS integration, can handle the higher computer memory volume demands of longer time series data, and could handle a greater number of parameters as well as the increasingly more complex management scenarios. In the OOP approach, modelling tools are easily integrated with the input processing and output analysis objects that are developed separately before integration into the main model framework. All the separate software objects can easily be utilised in other models when the need arises. The HYDRO25 model uses modular objects and a visual-based programming language that easily accommodates integration with other software objects based on the component object model system. This has made further upgrading and redevelopment of the model easy to handle.

In this study, the HYDRO25 model was developed and used in the Doring River catchment as a case study which was aimed at providing first-hand information about model development and application in South Africa. In the HYDRO25 model, computer code was used systematically to handle the catchment hydrology, geographical information, climatic factors, water use, catchment development proposals, the requirement of water legislation, and other factors to provide information that is useful for decision-making.

In the Doring River case study, proposed irrigation developments in the Koue Bokkeveld and Aspoort area of the Western Cape were assessed using the HYDRO25 model to determine the most viable development options from a hydrological perspective. The study showed that the full irrigation potential of the catchment cannot be utilised with the available surface water resources in the catchment. The model simulation results showed that a maximum of 700 hectares can be irrigated in the Koue Bokkeveld area without creating additional water storage. Analysis of the Aspoort irrigation scheme showed that the irrigation area should be limited to 1000 hectares, with the proposed 178 million m^3 Aspoort Dam being developed to support irrigation water demand and, to a small extent, to contribute to other water uses in the catchment, such as ecological flows and domestic uses.

Opsomming

Die beskikbaarheid van voldoende inligting is een van die basiese vereistes vir doeltreffende waterbronontwikkeling. Eenvoudige alternatiewe vir die ontwikkeling van waterbronne, waar minder uitvoerige ondersoeke benodig word, is reeds ontwikkel, en wel tot so ‘n mate, dat ontwikkelingsvoorstelle deesdae meer indringende en omvattende navorsing vereis. Hierdie ondersoeke genereer onder meer inligting oor die hidrologiese risiko wat gepaard gaan met die implementering van waterbronprojekte. Die modelleringshulpmiddels wat gebruik word om inligting oor waterbronne te verkry word gewoonlik gekompliseer deur die betrokkenheid van talle veranderlikes wat met mekaar verband hou en gewoonlik onvoorspelbaar is. Die onlangse Waterwet (Republiek van Suid-Afrika, 1998) beklemtoon die behoefte aan geïntegreerde waterbronbestuur, billikheid en ekologiese volhoubaarheid - aspekte wat nuwe dimensies verleen het aan waterbronbeplanning. Simulasiemodelle vir wateropvanggebiede wat al die verskillende dimensies van waterbronbeplanning in ag neem en wat meer inligting as ooit tevore tot die beskikking van besluitnemers stel, het die hulpmiddels geword wat voorkeur geniet.

Hoewel vroeëre hulpmiddels vir waterbronbeplanning nog steeds algemeen gebruik word, het die studie getoon dat hierdie ouer hulpmiddels agter geraak het wat betref die ontwikkeling op gebiede soos nasionale wetgewing, waterbelanghebbendes se werksomgewing asook die snelle verandering in rekenaarsagteware en hardeware. Die geskiktheid van modelleringshulpmiddels vir waterbronne in Suid-Afrika is ondersoek in die lig van ‘n veranderende wateromgewing asook die behoefte om verskeie faktore wat uniek aan Suid-Afrika is, aan te spreek. Die waterbronfaktore wat ondersoek is, sluit onder andere in hidro-klimatologiese, waterinstitusionele raamwerke en die behoeftes van belanghebbendes, beskikbare kundigheid en die tegnologiese aspekte van die beskikbare waterbestuur- en beplanningshulpmiddels. Op grond van die uitslae van die ondersoek na Suid-Afrika se unieke wateromgewing, is aanbevelings en riglyne ontwikkel met die doel om ‘n voorkeurscenario vir plaaslike waterbronmodellering daar te stel.

Hierdie studie ondersoek en beveel die gebruik aan van modelle vir waterbronstelsels wat gegrond is op die jongste modellering- en IT ontwikkelings, soos HYDRO25 vir die multi-kriteriabeplanning van geïntegreerde waterbronne. In hierdie studie word die ontwikkeling van objekgeoriënteerde programmeringsmodelle met visuele koppelvlakke wat by die gewilde Windows bedryfsomgewing inskakel, onderskei as 'n kernaspek van waterbronmodellering. Hierdie modelleringsaanslag is geïdentifiseer om hulpmiddels daar te stel wat meer gebruikersvriendelik is, wat visuele leidrade verskaf na aan die werklike stelsel, insluitende GIS integrasie, wat die groter vereiste vir rekenaargeheuevolume van langer tydreekse se data kan hanteer en wat 'n groter aantal parameters kan behartig, asook die toenemend meer ingewikkelde scenarios. Met die benadering van objekgeoriënteerde programmeringsmodelle word die modeleringshulpmiddels maklik geïntegreer met die sagteware vir die insetteprosessering en die uitsetanalise wat as afsonderlike objekte ontwikkel word alvorens hulle saam met die hoofmodelraamwerk geïntegreer word. Die HYDRO25 model maak gebruik van modulêre objekte en 'n visueel-gebaseerde programmeringstaal wat die integrasie met ander sagtewareobjekte, gebaseer op die komponent-objekmodelsisteem, maklik kan behartig. Dit het die verdere opgradering en herontwikkeling van die model makliker gemaak.

In hierdie studie is die HYDRO25 model ontwikkel en in die Doringrivieropvanggebied as ontledingstegniek gebruik. Dit was daarop gemik om eerstehandse inligting oor modelontwikkeling en die toepassing daarvan in Suid-Afrika te verskaf. In die HYDRO25 model is rekenaarkode gebruik om waterbronveranderlikes in 'n opvanggebied sistematies te hanteer, insluitende die hidrologie, geografiese inligting, klimaatsfaktore, watergebruik, ontwikkelingsvoorstelle vir die opvanggebied en waterwetgewing ten einde inligting beskikbaar te stel wat nuttig is vir besluitneming.

In die Doringriviergevallestudie is die voorgestelde besproeiingsontwikkeling in die Koue Bokkeveld en die Aspoortgebied van die Weskaap beoordeel met behulp van die HYDRO25 model ten einde die mees lewensvatbare ontwikkelingsopsies vanuit 'n hidrologiese perspektief te bepaal. Die studie het getoon dat die volle besproeiingspotensiaal van die opvanggebied nie verwesenlik sal kan word met die beskikbare oppervlaktewaterbronne binne die opvanggebied nie. Die resultate van die modelsimulasies het aangetoon dat ‘n maksimum van 700 hektaar in die Koue Bokkeveldgebied besproei sal kan word sonder die daarstelling van bykomende wateropgaarfasiliteite. ‘n Ontleding van die Aspoortbesproeiingskema het aangetoon dat die besproeiingsgebied tot 1 000 hektaar beperk moet word, terwyl die voorgestelde 178 miljoen m^3 Aspoortdam ontwikkel word om in die vraag na besproeiingswater te voorsien, en, in ‘n mindere mate, om ‘n bydrae te lewer tot ander watergebruike in die opvanggebied, soos ekologiese vloeie en huishoudelike gebruik.

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ACRU	Agricultural Catchments Research Units
API	Application Programming Interface
ARC	Agricultural Research Council
ARSP	Acres Reservoir Simulation Programme
BASINS	Better Assessment Science Integrating Point and Non-Point Sources
BOD	Biochemical Oxygen Demand
CCWR	Computing Centre for Water Research
CMSs	Catchment Management Strategies
CSIR	Council for Scientific and Industrial Research
DEAT	Department of Environmental Affairs and Tourism
DEMs	Digital Elevation Models
DHI	Danish Hydraulic Institute
DO	Dissolved Oxygen
DSC	Dead Storage Capacity
DST	Department of Science and Technology
DTMs	Digital Terrain Models
DWAF	Department of Water affairs and Forestry
EPA	Environmental Protection Agency
ESRI	Environmental Systems Research Institute
EU	European Union
FME	Feature Manipulation Engines
FSC	Full Supply Capacity
GDP	Gross Domestic Product
GIS	Geographical Information Systems
HBV	Hydrologiska Byråns Vattenbalansavdelning (Hydrological Bureau Waterbalance-section)
HIV/AIDs	Human Immunodeficiency Virus / Acquired Immune Deficiency Syndrome
HRU	Hydrological Research Unit
HTML	Hyper Text Mark-up Language
HYCOS	Hydrological Cycle Observing Systems
ICOLD	International Commission on Large Dams
IFR	In-Stream Flow Requirements
IMWI	International Water Management Institute
IT	Information Technology
IUCN	International Union for the Conservation of Nature
IWRM	Integrated Water Resources Management
KBV	Koue Bokkeveld
LAS	Large Aperture Scintillometer
LHWP	Lesotho Highlands Water Project
MAP	Mean Annual Precipitation
MAR	Mean Annual Runnoff
MBB	Model Building Blocks
MDGs	Millennium Development Goals
MCP/PMT	Multi-Criteria Performance /Productivity Measurement Technique

MS	Microsoft
NEPAD	New Partnership for Africa's Development
NGA	National Groundwater Archive
NGDB	National Groundwater Database
NIS	National Information Systems
NSIF	National Spatial Information Framework
NWA	National Water Act
NWRS	National Water Resource Strategy
OLE	Object Linking and Embedding
OO	Object Oriented
OOP	Object Oriented Programming
ORDP	Orange River Development Project
ORRS	Orange River Replanning Study
POSC	Petrotechnical Open Software Corporation
PROMETHENE	Preference Ranking Organisation METHod for ENrichment Evaluation
PWV	Pretoria-Witwatersrand-Vereeniging
QUALDB	National Water Quality Database
RADAR	Radio Detection and Ranging
RDMs	Resource Directed Measures
RMSE	Root Mean Square Error
RQOs	Resource Quality Objectives
RRR	Rainfall-Runoff Relationship
SADC	Southern African Development Community
SASA	South African Sugar Association
SAWS	South African Weather Service
SBEEH	School of Bioresources Engineering and Environmental Hydrology
SCS	Soil Conservation Services
SDSS	Spatial Decision Support Systems
SFRAs	Stream Flow Reduction Activities
SIDA	Swedish International Development Agency
SOTER	Soil and Terrain
TIN	Triangular Irregular Network
TWP	Thukela Water Project
USGS	United States Geological Survey
VRS	Vaal River System
WfW	Working for Water
WMA	Water Management Area
WMO	World Meteorological Organization
WRC	Water Research Commission
WRM	Water Resources Management
WRPM	Water Resources Planning Model
WRS	Water Resources System
WRYM	Water Resources Yield Model
WSAM	Water Situation Assessment Model
XML	e**X**tensible **M**ark-up **L**anguage

Chapter 1

Introduction

1.1 General background

The study of water resources requires an assembly of several scientific disciplines that examine components of the hydrological cycle and evaluate the degree to which human intervention can derive benefits for society. There is a rising need for more comprehensive inputs from different scientific disciplines as the pressure on limited water resources continues to escalate. Falkenmark, de Sherbinin, and Dompka (1996) pointed out that the world's water supplies are continuing to dwindle because of resource depletion and pollution, whilst water demand is rising fast because population growth is coupled with rapid industrialisation, mechanisation and urbanisation. South Africa is one country where water demand in many areas has already exceeded the available water supplies and progressively larger volumes of water have to be transferred from those catchments where water is still available (Basson, 1998; Ashton and Haasbroek, 2000).

In addition to the inadequate state of the present water supplies, the South African Government is implementing the National Water Act (Republic of South Africa, 1998) where new approaches are being utilised in the development, operation and management of water resources. Of importance in the changes sweeping the water sector is the fact that while new legislation is coming into the water sector, the political climate is also going through extensive changes, affecting sectors that were dominated by inequalities. The water sector, with a previous legislation that linked water rights to land ownership has noted the need for extensive restructuring that, in many cases, has put pressure on practitioners in water resources management (WRM), to provide information that is more closely linked to the water sector changes to assist the decision-makers. Dent (2000) pointed out that in southern Africa the practice of water resources management has moved in step with the societal needs of the region over the past decades. These needs have passed through phases which placed more emphasis on "getting more water", than "using water more efficiently". Dent (2000) points out that the dominant theme now is "allocating water equitably".

Developments in the WRM field have focused on the development of an Integrated Water Resources Management (IWRM) approach (Walmsley *et al*., 2001). The concept of sustainability is identified as a key to the measurement of the successes of the implementation of the new South African Water Act. Wamsley *et al*. (2001) explore a number of indicators of sustainability in terms of the water resources managed by different organisations. In the Murray-Darling basin, a major catchment in Australia, the sustainability plan is "to promote and co-ordinate effective planning and management for the equitable, efficient and sustainable use of water, land and other environmental resources of the catchment". The Fraser Basin Council of Canada had another interesting vision on sustainability in its charter which states that: "the basin is a place where social well being is supported by a vibrant economy and sustained by a healthy environment". In the national water policy of South Africa, the term "resource quality" is used to summarise environmental sustainability where it is used to include the health of all parts of the water resource that make up an ecosystem, including plant and animal communities and their habitat (DWAF, 1997d).

In South Africa, most of the water used in water provision schemes comes from surface water resources. The consumption of water in South Africa exceeds 10 000 million cubic metres (m^3) per annum, of which 90 % is derived from flowing rivers and storage dams. The mean annual runoff of the country as a whole was estimated in 1999 to be 60 000 million m^3 (DWAF, 1999). Most urban settlements in South Africa have already exhausted their own catchment runoff yields and are now relying on water transfers from adjacent catchments (Basson, 1998). The Pretoria-Witwatersrand-Vereeniging (PWV) area is a typical example of a case where there are already four schemes pumping water from other catchments. The four schemes pump a total of 840 million m^3 per year into the Vaal River catchment. A number of projects to transfer more water from other catchments to the Vaal River are also under investigation. Additional transfer schemes under investigation include the Thukela, Umzimvubu, Caledon River and Phase 2 of the Lesotho Highlands Project (DWAF, 1999). The volume of these additional water transfers to the Vaal River is presently equivalent to 40 % of the natural inflow to the Vaal Dam, and is expected to reach 150 % of the natural flow in the early 2020s when further transfer schemes are completed (Basson, 1999; McKenzie, 2000). Against this background, the country has seen the use of a range of sophisticated water management tools to co-ordinate, manage, plan and serve the water requirements of a number of water using activities. Recent examples of extensive use of modelling tools in water management in South Africa include the Orange River Replanning Study (ORRS) (DWAF,1999) and the Thukela Water Project (DWAF, 2001a).

However, the development and use of water resources planning and management models in South Africa lacks clearly defined guidance. The need for guidance in water resources planning and management especially in the development and use of models is motivated by the following:

- Water resources model development and use has been done in a non-integrated and unguided manner, resulting in the proliferation of many tools in different institutions, developed and used by many different individuals. Most efforts did not compliment existing tools, but were mere repetitions resulting in wasted resources and sometimes conflicting outputs. Lack of a single voice in deciding which models to use and how to use them is a common occurrence as evidenced in motivations for some of the research proposals submitted to water resources research funders (WRC, 2003a).

- Most of the water resources modelling tools in southern Africa were developed in response to specific needs with little consideration of the need for their integration. Integration, as expressed in the National Water Act of 1998 (NWA), is now the preferred route of water resources management in South Africa.

- Increased water demands, coupled with the continuously dwindling water resources and other impacts of years of water management under South Africa's 1956 Water Act (South Africa, 1956) and its replacement in 1998 (Republic of South Africa, 1998), have meant a shift of focus and principles behind the management of water resources.

- The unavoidable need to import solutions developed in other countries for use on local problems requires guidance to ensure that the processes followed complement and add value to national initiatives. The outcomes of water management solutions in other countries indicate the need for customised solution development in each country, so that they are not mere duplicates from other regions, countries or continents. Shah, Makin and Sakthivadivel (2000) pointed out that developed countries have taken decades and in some cases hundreds of years to develop their water resources management and planning approach to where they are now. Commenting on the application of solutions from the developed world, Shah *et al.* (2000) pointed out that developing countries face difficulties in making such a "leap-frog" because of the vast and fundamental differences in five realities that matter in their institutional evolution. These realities were listed as: hydrological and climatic characteristics, demographic patterns, socio-economic features, historical influences and the way their water sectors are organised. Water resource "leap-frog" initiatives, such as transferring the lessons of success in integrated river basin management from the Murray-Darling basin to the Mahaveli basin, and the Mississippi basin to the Mekong basin, have attempted to feed into programmes targeted at fasttracking water sector changes in the developing countries.

- Water management and planning boundaries and the understanding of solutions are continuously changing. Some important changes include the need to move away from solutions that only target increased supplies of water, and look for solutions that enhance both supply and demand management options (DWAF,1998b). On the other hand, the predominantly scientific and engineering solutions need to be replaced or improved to incorporate new high priority factors such as social, economic, political and stakeholder issues.

- Transboundary water management in South Africa has also changed towards a tendency to seek more peaceful and cooperative handling of transboundary waters (Turton, Nicol and Earle, 2003). The sharing of information openly as expressed in the NWA means that neighbouring countries can be well informed and, ideally, are part of decisions made on these river basins that they share.

- South Africa, like most developing countries, is going through a period when the knowledge resources, technology and expertise are improving dramatically. These improvements mean that older solutions and modelling tools are less preferred and in some cases they are no longer valid because they can not provide the types of solutions that are required. Major Information Technology (IT) developments in recent years have introduced new possibilities and completely new approaches that have changed the positioning of modelling tools in the water sector.

- Other changes in South Africa such as land use, population demography, establishment of CMAs, revised definitions of water uses, and reallocation of water as provided for in the NWA, are bringing new challenges to the management and planning of water resources.

1.2 The growing "water problem" in southern Africa as it applies to modelling

"Water is ubiquitous. No place on earth is whole without water" (Barney, 1980). Of all substances found on earth, water and air are the most critical and significant for the existence of life. Unlike air, water distribution and its availability causes a major threat to life. Water has the ability to wipe out whole generations if improperly utilised, managed, or planned for. As an example, floods and droughts destroy lives and livelihoods in areas where suitable precautions have not been taken to avoid the devastating effects of these phenomena.

Long-term rainfall trends over the past hundred years have shown insignificant changes in southern Africa; however, recent years have been noted to have a consistent shift towards increasing probability of extreme rainfall events (Fauchereau, Trzaska, Roualt and Richard, 2003). The widespread flooding across much of southern Africa in 2000 due to Cyclone Eline, displaced more than a million people and left about 700 people dead as flood waves in the Limpopo basin peaked to levels higher than the two hundred year return period (Artan, Restrepo and Asante, 2002).

Urban migration and other population redistribution factors, as well as the impacts of the deadly Human Immunodeficiency Virus / Acquired Immune Deficiency Syndrome (HIV/AIDs) pandemic in southern Africa are also changing the water demand patterns. Studies by Ashton and Ramasar (2002); and also Kamminga and Wegelin-Schuringa (2003) reported that uncertainties surrounding forecasts of HIV/AIDS-related mortality and population growth rates are complicating the planning and implementation of water supply and sanitation systems. The general trend is that population growth rates and life expectancy are both plunging but the people's need for clean and sufficient water and sanitation has become even more acute. More informed solutions to deal with water management and planning such as integrating approaches to increase water supplies with the improvement of demand management are receiving greater preference from decision makers (DWAF, 1998b).

Water management problems are complex in the ecological domain, and often become controversial when socio-economic issues are incorporated in decision making (Poch, 2002). This has been the case in southern Africa's water resources management and planning where decision makers have embraced some preferred international trends that seek to integrate water quantity and quality in both surface and groundwater, social factors, economic issues, legal and political aspects as well as stakeholders' expectations in the development of solutions. Typical examples include the recent water legislation changes in both Zimbabwe and South Africa in the late 1990s. Other challenging initiatives in southern Africa have come about through the need to work towards recently agreed international goals on water and sanitation such as the recent resolution at the World Summit on Sustainable Development in Johannesburg in 2002, where it was resolved to work towards halving the number of people without access to clean water by the year 2015. In southern Africa, which is home to some of the poorest communities in Africa, such resolutions are mammoth tasks requiring significant resource inputs beyond the regional capacity. In the case of South Africa, a more specific target is to provide clean water to approximately 6 million people who currently lack access to reliable and wholesome supplies of water by 2008 (DWAF, 2003b).

Southern African countries are poorly equipped to deal with current problems, such as the famine facing more than ten million people (IFPRI, 2003). As a result, short-term "fire-fighting" responses designed to address immediate problems are common. Few resources are left for longer-term planning in general. Water resources model development is inevitably placed low in national priorities when compared to the urgency of many other needy situations such as the current water and food shortages in most southern Africa countries. These are also coupled to the increased frequency of extreme climatic events such as droughts and floods (IFPRI, 2003). The limited availability of resources has meant that developed solutions are poorly researched and often case-specific, such that they fail to deal with the complex real life situations. Parkinson (2004) pointed out that the days of building a new model to answer a new question are numbered. Rather than addressing single issues a catchment manager will want to know the overall effects of, say, pursuing a given policy. For example, a new reservoir will affect the downstream flow regime, which in turn, will affect the river's ecology, the tourism based on the fishing, and ultimately, the whole local economy.

Another, worrying trend is the migration of local expertise to developed countries (DST, 2002). This has left southern Africa grappling with insufficient capability to deal with problems that require expert solutions, such as water resources modelling tools. Dent (2000) pointed out how water resources modelling in South Africa has lagged behind developments in other areas of Information Technology; he said: "In terms of the PC analogy, the South African water resources modelling industry is in the pre-DOS era".

Another noted problem is that water consumption has risen steadily over the years. Virtually every country in the world today faces severe and growing challenges in their efforts to meet the rapidly escalating demand for water resources that is driven by burgeoning populations (Ashton and Haasbroek, 2000). On the other side, water resources depletion and pollution are cited to be causing a steady decline in the quantities of available water resources (Barney, 1980). In southern Africa, the spatial distribution of water resources seldom matches the needs of the communities and countries concerned (Basson 1988; Ashton, 2000; DWAF, 2001b). Ashton (2000) examined the availability and distribution of water resources across the African continent and concluded that there are "hot spots" where water-related conflicts are imminent and that there is need to take preventive measures if conflict is to be avoided. Basson (1988) cites that, in the case of South Africa, the majority of the economic activities of the country, as well as over 40 percent of the population, are concentrated in the PWV area, while the distribution of the water is such that the major reserves are found in locations that are distant from where it is required. The result of this has been that the development of water resources for the major urban and industrial centres of South Africa has influenced water yields from many other catchments. The complex interrelationships of the integrated water supply system consisting of several catchments, necessitate the use of advanced computer models and analytical techniques to ensure successful planning of future developments as well as ensuring the optimal operation of the existing system. In

DWAF (1999), a water resources planning process that involved extensive modelling was developed to provide information on questions surrounding further water transfer schemes to the Vaal River system. In the DWAF (1999) study, the ORRS, a typical model solution to the problems of managing water resources was developed.

International influences in southern Africa's water management processes brought in water management reform agendas which seldom coincide with existing agendas. These reforms are usually tailor-made to work towards economic profitability and most of these reforms are not sustainable when the existing socio-economic, cultural and political factors are brought in. A typical example of a socio-economic and political decision that is completely out of tune with imported water sector reform agendas is the recent Free Basic Water Policy in South Africa. This policy calls for the provision of up to 6 m^3 of potable water, free, to all households per month (Kasrils, 2003). Many municipalities that are struggling with other reforms find this policy difficult and costly to implement. According to Dinar (2001) "A reform program will be successful if there is economic rationality in its design, political sensitivity in its implementation, and close and constant attention to political-economic interactions and social-institutional factors [during its implementation], so as to determine in each case the dynamics to follow." Talking of reforms from the developed world Kasrils (2004) said: "The North/South, Rich/Poor, Win/Lose solutions of the developed world are not sustainable even for the North and the Rich."

Southern Africa has inadequate human, financial and technology resources in the IT sector. In water resources planning and management, this problem is aggravated by the existence of many other visible needy situations that usually receive higher priority in resource allocation due to their nature; for example, as human catastrophes in the case of unanticipated floods and droughts. Information Technology solution developments in the water sector require reliable funding, good data, suitable management and planning tools, appropriate expertise, suitable information dissemination platforms and many other components that are not readily available in southern African countries. Decision-makers are also consistently being coerced into using modelling solutions from developed countries through aid funding packages that do not address the underlying socio-economic problems, or develop long-term sustainability.

1.3 Study objectives and methodologies

This study seeks to correctly place surface water resources modelling as a key decision-maker's tool for water resources planning and management. Modelling is discussed in this study as a modern and dynamic IT-based source of information and insight for addressing water resources planning and management problems.

The study aims to present water resources modelling as a tool that has benefited from recent developments in the water sector and the IT industry, such as the emphasis on integrated water resources management, the use of user-friendly graphical interfaces, and the increased memory capacity of computer hardware. Unlike the majority of models in current use that have such a high level of complexity that only a few individuals ever develop abilities to use them, this study will try to "demystify" water management modelling to broaden its use at all stakeholder levels. This study also aims to bring the water management practitioner to a level where the water modelling problem is not only a problem that he/she seeks to simulate, but rather seeks to customise existing simulation tools or develop new tools that best fit within the particular characteristics of the problems being resolved in his/her specific water management situation. In this study, current practices in surface water modelling are evaluated, and a model development process that simulates a typical water management problem based on recorded data is examined in detail.

This study targets surface water resources as its main focus, without excluding an appreciation of interactions within the hydrological cycle, and correctly placing the surface water resource in this cycle. The focus in this study has been set on surface water resources due to the importance of this resource to South Africa where it contributes approximately 85% of all water use (DWAF, 1986). A surface water resources perspective was also selected to take advantage of the author's interests and experiences in this area. While the study focuses on surface water, other water resources such as ground water were accounted for in the integrated perspective, especially the modelling processes and water balances.

In this study, the investigations and evaluation of existing tools and trends, as well as a case study on model development, are used as a basis to formulate a framework for guiding water resources modelling in South Africa. The problems investigated in the case study focus on the problems surrounding the development of models and their use in determining water yield, and the hydrological feasibility of large-scale irrigation schemes which are major issues in most catchment-based decision making processes.

This study investigates the current and historical status of water resources modelling in South Africa and abroad. These investigations identify the unique features in South Africa which point to the need for specific solutions when addressing local water resources management and planning. Local and international modelling trends and initiatives will be investigated and compared. The findings are used as a basis for a framework for preferred model development and use in South Africa.

A water resources management model is developed in this study and applied to a typical South African study catchment. The development of the model and its application on a typical catchment are set to provide information on the following areas:

i) Currently existing frameworks to guide model developers in South Africa,
ii) Comprehensiveness, effectiveness and robustness of local model developments,
iii) Model development constraints that hinder the development and use of models in local surface water management,
iv) Model applicability and acceptability in addressing South African problems,
v) Data availability and its processing in surface water management where water resources modelling is applied,
vi) The use of Geographical Information Systems (GISs) and Digital Terrain Models (DTMs) in water management solutions,
vii) User support, window interfaces and the required levels of "feel and touch" aspects in modelling,
viii) Model calibration techniques that emphasise automatic calibration, and
ix) Model development and use guidance requirements.

The findings from the status and trend investigations on water resources modelling as well as the model development, are used to draft the framework for guiding future water resources model developers.

1.4 Layout of the thesis

This report documents an investigation and recommendations for surface water resources planning and management methods, especially computer-based modelling, in South Africa. References to broader water resources management and planning in other African and overseas countries are made to illustrate current trends and practices in water resources decision making tools.

This thesis is divided into four main sections. The first section contains three chapters and presents a detailed literature review as well as an update on water resources modelling approaches. The three Chapters contain a detailed introduction (Chapter 1), a literature review on water resources planning and management (Chapter 2) and a literature review and update on South Africa’s unique features in water resources modelling (Chapter 3). In Chapter 3, the methods of water resources modelling used in South Africa are characterised by a number of features that address the country’s unique qualities. In this Chapter, these unique qualities are explored to provide guidance on how they should be addressed in future water resources management and planning models.

In Section 2, recommendations and guidance on water resources modelling are presented and discussed. Section 2, is based on the outputs of the literature review presented in Section 1, as well as a review of additional literature that provides specific recommendations for ideal methods of water resources modelling. Section 2 contains four Chapters, consisting of Recommendation and Guidance on Water Resources Modelling (Chapter 4); Model software selection and development (Chapter 5); Verification, Calibration and Validation (Chapter 6) and Spatial data and stakeholder inputs in water resources modelling (Chapter 7).

Section 2 includes the investigation of surface water resources planning and management methods and a practical investigation of local water resources model development and application, where the model HYDRO25 was developed and applied on the Doring River catchment. The development of the model HYDRO25, which is reported in Appendices I and II, as well as its use in the Doring River catchment, were set up as a case study to support the investigation of local water resources model development and application.

Section 3 presents the case study on water resources model development and application in three chapters. Chapter 8 presents an introduction and a summary of the HYDRO25 model development, with further information on the model development in Appendix I, and details of the model application in Appendix II. In Chapter 9, model calibration, verification and catchment simulation issues are discussed. Chapter 10, the last chapter in Section 3, discusses the results of model application in the Doring River basin.

The conclusions made and the recommendations arising from this study are presented in Chapters 11 and 12 comprising the fourth and final section of this Thesis.

1.5 Water resource modelling trends

1.5.1 South African trends in water resources modelling

The lessons of the past are the foundation of decisions that are made now and those that will still be made in the future. Schilling (2002) points out that there is an unfortunate lack of understanding of previous trends in water resources management theory, planning and practice, which impacts negatively on our current approaches. He expressed the view that the water industry is increasingly failing to utilise past lessons and experiences to guide new initiatives.

The first personal computers came into use in the early 1970s. These computers had limitations in terms of low processing speeds, very little hard drive memory space, and inadequate random access memory. Most locally developed water resources management models had their initial life during the 1970s. Water resources models in the 1970s were short and simple as developers also had to work within the limitations of the computing environment of the time. An important early water resources computational tool is presented in the Hydrological Research Unit (HRU) report 2/69 (Midgley and Pitman, 1969) where a means of making first order estimates of storage requirements to meet a desired water demand at a specific assurance level was reported. Further developments to this work involved the inclusion of the Rainfall-Runoff simulation (Pitman, 1973) and the inclusion of reservoir, irrigation and afforestation simulations (Pitman, Kakebeeke and Bailey, 2001). These developments led to the development of the monthly model which is now referred to as WRSM2000. The ACRU model, a daily South African agro-hydrological model named after the Agricultural Catchments Research Units had its origins in a distributed catchment evapotranspiration based study carried out in the Natal Drakensberg in the early 1970s (Schulze and Pike, 2004). The agrohydrological component of the ACRU model first came to the fore during research on an agrohydrological and agroclimatological atlas for Natal (Schulze, 1996). A Windows version of this model was completed in 2003 (Schulze and Pike, 2004).

The models developed in the 1970s and 1980s were dominated by text-based interfaces on monochrome screens. These models have continued to retain some of their original set-up which no longer meet current user needs and are not suitable for interfacing and coupling with more recent versions of programming software. The use of old software to solve today's problems 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".

In 1992, R. B. Allen of Acres in Canada brought to South Africa the Acres Reservoir Simulation Programme (ARSP) and his expertise as the original developer of this model. Using the ARSP model as the basis, R. B. Allen teamed up with the engineering consulting company, BKS and the Planning Section of the Department of Water Affairs and Forestry (DWAF) over the next five years to develop two new water resources models, the Water Resources Yield Model (WRYM) and the Water Resources Planning Model (WRPM) (McKenzie and van Rooyan, 1998). The two models utilise an Out-Of-Kitler network solver (Basson, 1988) that is based on a penalty system defined through user inputs to describe the natural water flow processes, abstractions, loses and reservoir operation rules. In both the WRYM and WRPM models, water system operating rules can be changed through external data files without changing the source code (McKenzie and van Rooyan, 1998). The WRYM is used first to determine the long-term yield of a catchment for defined risk levels. The WRPM is usually used in the second stage of a water system analysis and allows the input of stochastic hydrological data for future projections and to determine the potential implications of different water system operation regimes. One of the most significant and important developments incorporated in the two models is the Stochastic Flow Generation Routines (Pegram, 1986). These routines which resolved major inadequacies in the time series data, which was usually patchy and of short duration, often spanning periods less than the required 30 years. The WRYM and the WRPM are presently being updated to incorporate more user-friendly routines, error handling routines, Windows interfaces and GIS.

During the 1990s, considerable work was undertaken internationally to develop standards for the digital compression of audio signals and both still and moving images (Meier, 2001). The simple personal computer of the early 1980s has now been transformed from essentially a text-based device to a high performance multimedia platform. Text, still images, graphics, video and audio can now be generated, manipulated and stored by the personal computer. The use of multi-media in models is preferred by most stakeholders with Windows operating systems. It is now very rare to find anyone using the MS-DOS text commands that dominated earlier models (Hughes, Boroto and Viljoen, 2004).

The NWA came with the National Water Resources Strategy (NWRS), which provides the framework in which DWAF will manage South Africa's water resources (DWAF, 2002a). This strategy is based on the principles of equity and sustainability, as well as efficient and effective water use. The NWA states that South Africa's water resources must be protected, used, developed, conserved, managed and controlled in accordance with the strategy. Local water resources management and planning tools are currently being updated or redeveloped to accommodate the requirements of the South Africa's NWRS.

While the bulk of the water volumes in South Africa are supplied through the formal water sector, most water users obtain their water through informal systems. Shah *et al.* (2000) point out that governance of water is complex in cases such as South Africa, where institutional reforms are challenged by the need to translate water law and new policies to reach many previously marginalised black communities, without creating much uncertainty among private investors. The water sector reform process in South Africa is still struggling to incorporate all stakeholders. The process of forming Catchment Management Agencies (CMAs) is revealing major stakeholder participation obstacles as Merrey (2000) realised in the formation of the Olifants Catchment Management Agency, where he said:

> *"..rural communities were unaware of the provisions of the new water law and the CMA process, despite the efforts to inform people and offer them opportunities to express their views. Small-scale farmers had not heard about the CMA... [But] the Irrigation Boards providing water to large commercial farmers were participating actively in the process.."*

McKinney, Cai, Rosegrant, Ringler and Scott (1999) pointed out that the single-objective, single-purpose, and single facility project approach to solve water resources problems that was common in many developed-countries' water planning agencies in the past, has gradually been replaced by multi-objective, multipurpose, and multi-facility solutions at the river basin level requiring multi-criteria modelling. In the case of South Africa, McKinney *et al.* (1999) pointed out that much effort has been invested in the modelling of separate components in river basin systems and that more effort is now required to combine these components into an integral system. The integrated approaches pursued in South Africa aim at developing solutions which are multi-objective, multipurpose, and multi-facility as provided for in the NWA. However, solution developers still rely on outdated modelling tools as they continue to seek to add other components rather than redeveloping well-integrated approaches. According to McKinney *et al.* (1999) the resulting solutions are not integrated, but usually run in compartments or sequentially, as they involve the addition of components that run using outputs from previous component runs. McKinney *et al.* (1999) pointed out that integration in modelling involves tight connections in model components where information transfer is conducted endogenously with data and parameters residing on common platforms. Single-objective, single-purpose and single facility approaches are also a result of the narrow views of the research teams who, in many cases, find it difficult to incorporate other players from different disciplines in their work. Research funding organisations are now seeking to work with consortiums of research groups through projects that are set up to utilise the strength of multidisciplinary approaches (WRC, 2003a).

Catchment management in South Africa is largely focused on river basin level initiatives to ensure that water is used in the most economical manner possible, and that allocation decisions are taken in a transparent and objective manner. However, there is little or no involvement of poor rural or urban communities, with most of the allocation issues being handled at large scale agricultural and industrial water use (Moriarty, Batchelor, and van Wijk, 2001). This approach has meant that most decision making tools have been biased towards large temporal and spatial scales.

The NWA brought with it new goals in water management, which have to be incorporated into the models developed for local use now and in the future. This entails the incorporation into models of revised definitions of water use such as Reserve water, Stream Flow Reduction Activities (SFRAs) and Environmental flows (In-stream flow, and River maintenance flows, and ecological flows). In the NWA, the minister can declare a SFRA for the purposes of licensing and charging the consumer. Forestry has been declared an SFRA for which users are required to apply for a licence and will be charged for usage. Other water-using activities, such as dry-land sugarcane plantation, are already being considered for SFRA declaration (Bosch and Warren, 2003). Developers of water resources management models and model users are busy finding methods of incorporating these legal requirements and water use definitions into the local water management and planning processes.

The issue of temporal and spatial scales in water resources management and planning models is one area that requires significant knowledge to advise local model developers, researchers and users. While it is clear that the developed countries are working towards smaller scales in time and space, the same cannot be said of South Africa. The NWA introduces more decision-making at Water Management Area (WMA) level, which is a smaller scale than the usual quaternary catchment and river basin level. On the other hand, the limited availability of finer-scale data in the country make it difficult to develop or use very detailed models that are suitable for such fine scales. Indeed, instead of installing more data recording stations and collecting higher resolution data, there has been a general decline in the number of recording points (Gill, 2004). A typical area of concern is the number of rainfall gauging stations which are known to have declined as shown in Figure 3.1.

Most of the key modelling tools in current use in South Africa were coded in different versions of FORTRAN. The shift towards more user-friendly software, such as Windows-based packages and object oriented programming, is happening mostly on the user interfaces and other tools to aid user interaction, while the internal model code is left untouched. Researchers, model developers and users are slowly developing awareness of the need to have completely rewritten and upgraded tools using more recent software packages that allow better tool integration, easier user updates and easier interfacing with other model modules and tools. The University of KwaZulu-Natal's School of Bioresources Engineering and Hydrology has been working on a project to rewrite the ACRU model using JAVA script (Schulze and Pike, 2004). On the other hand, the original Pitman model which is in FORTRAN code now has a windows-based user interface added to it (Pitman, Kakebeeke and Bailey, 2001).

The use of GIS is quickly increasing in water resources management and planning software. GIS tools, such as Microsoft's Map-Objects software and the Environmental Systems Research Institute (ESRI)'s spatial analyst software are now considered as important components of water resources modelling. In South Africa, recent uses include DWAF's Water Systems Analysis Model (WSAM) and GIS Viewer programme, WQ2000 (Herold, 2003) and SPATSIM (Hughes, 2003). Wider use of GIS is still challenged by the high costs of software and their licences. For example, the current package of the commonly used GIS software in South Africa's water industry, ArcGIS, costs more than R193 000 (GIMS,2003). The continuous need to update to newer software versions and the widespread lack of knowledge on use of GIS are other common challenges. While there are many other GIS packages in the international market, in South Africa's water resources industry the term GIS is synonymous with ESRI software. According to McKinney *et al*. (1999) the approach in GIS packages in South Africa is loose coupling, as opposed to the more preferred tight coupling, in which simulation and optimisation models share the same database with the GIS and are imbedded in a single manipulation framework.

1.5.2 International trends in water resources modelling

The design and application of mathematical models to predict hydro-meteorological processes can be traced to Richardson in 1922 (McKinney *et al.*, 1999). The potential of computers to solve numerical models representing complex hydrologic processes was harnessed during the rapid expansion of the water resources infrastructure in the 1950s and 1960s. Given the computational limitations imposed by the available computer hardware and software at the time, the focus of early water resources models was primarily restricted to planning and design. However, the need to combine economic and hydrologic considerations in water resources systems was recognized at an early stage.

Expensive computer access and long run-times coupled with cumbersome input of often scarce data, ensured that models remained the exclusive domain of specialized users located in government and academic research institutions (McKinney *et al.*, 1999). Maxfield (1997) pointed out that that in 1975, an IBM mainframe computer that could perform 10,000,000 instructions per second cost around US$10,000,000. In 1995 (only twenty years later), a computer video game capable of performing 500 x 10^{12} (500 trillion) instructions per second was available for approximately US$500.

The initially high costs of computer memory limited the development of multi-objective, multi-purpose and multi-facility water resources modelling. The solutions developed in the 1970s were targeted to solve specific problems in defined study areas. Cases of dams being simulated as complete units without the river system were common. McKinney *et al.* (1999) reported that through the 1980s, river basin models focused on the functioning of the principal infrastructure component of most water resources management systems, the reservoir. As water quality deteriorated and water demand increased, solutions started to integrate water quantity and quality as well as an integration of surface and ground water solutions. On the other hand, development in countries meant that water resources management started to take into account socio-economic factors and environmental flow requirements, as well as complex multi-objective approaches that aimed at integrating as many factors as possible. These approaches have also been transferred to less developed countries using processes such as those described as water resources management "Leap Frog" by Shah *et al*. (2000).

With the advent of user-friendly personal computers, Windows-based interfaces, and public-domain information access during the 1980s, water resources models were rapidly developed, acquired and widely applied by private and public organizations. As both numerical representations and computers became more sophisticated, water resources model emphasis shifted from engineered systems with clearly defined decision and control variables, to natural systems in which human interventions were analyzed in a broader environmental systems context.

The advent of the internet in the 1990s brought in an era where software developed elsewhere could be downloaded freely by other users, and models could be developed using a larger skills base located in different parts of the world and often separated by vast distances, language barriers and time constraints (Schilling, 2002). Data collection improved in many countries while the numbers of users of available software that took advantage of the internet also increased. In the internet world, less-resourced model developers have been reduced to mere users and evaluators of water resources solutions that are developed elsewhere. The thinking in some sections of the water sector has been "Why don't you download a free copy of a similar model from the internet?" The internet has been responsible for the limited development of certain modelling tools and emergence of new problems. These problems include the use of inappropriate freely available models, lack of creativity as developers work around available tools rather than develop models as needed, limited understanding of the modelling processes, and the general deterioration of value attached to the modelling as less experienced and lower level personnel are assigned to work with the free models.

The developments of multi-use, tightly coupled and integrated water resources management tools that incorporate GIS, DTMs, socio-economics and multi-objective optimisation modules are now the preferred solutions. (Parkinson, 2003).

Integration in models has reached a level where solutions from individual points are simulated in conjunction with other points, within yet other spatial units which, together, make up a range of spatial scales and incorporate many parameters, GIS, DTMs, legislative frameworks, socio-economic routines, stakeholders preferences, etc. The simulations of fine-scale areas are integrated into catchments, river basins and, in some cases, regional simulation frameworks and models. Typical examples of the most recent integrated models include the approach in ArcHydro shown in Figure 1.1 below. The MIKE INFO Model also presents a well integrated platform for GIS, models, data and parameters as illustrated in Figure 3.6.

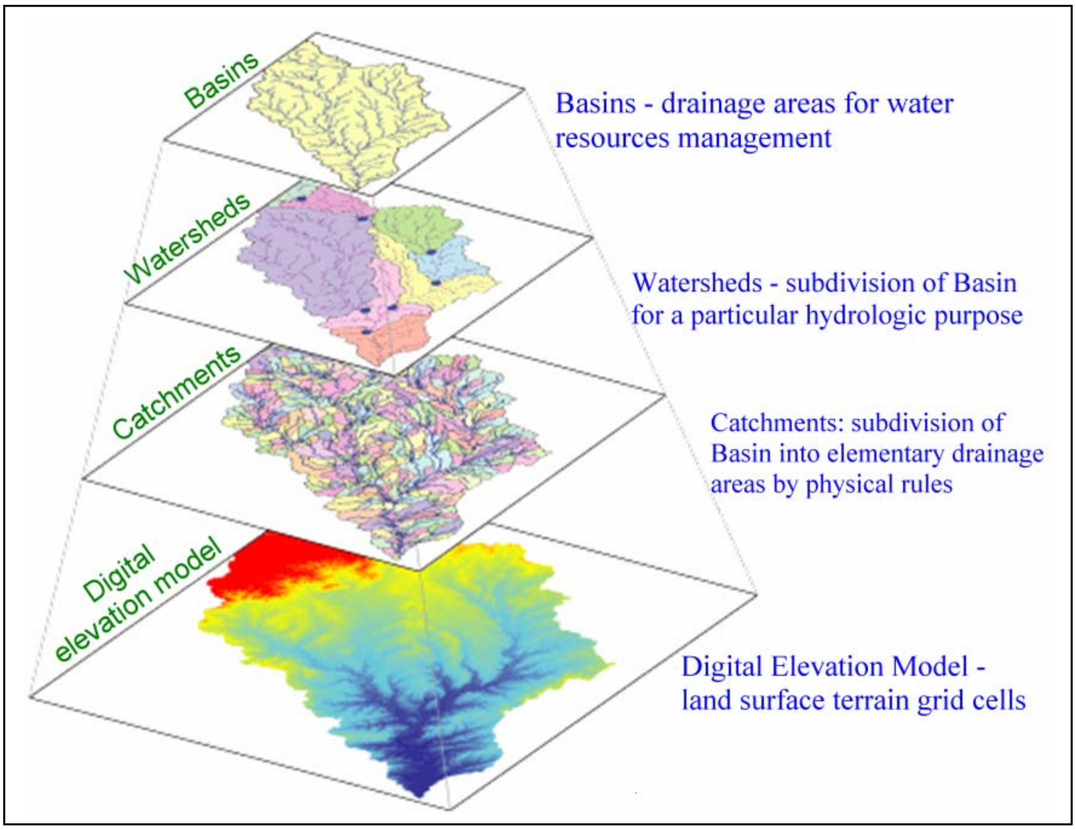


Figure 1.1 Scale of representation of drainage systems in ArcHydro (Redrawn from Maidment, 2001).

Other areas of recent developments in the water resource modelling industry are the growth of e-conference to facilitate the sharing of ideas and experiences by people working on a similar problem or using a single model but separated by vast distances (Vreke and McDevitt-Pugh, 2003). Water resources models that utilise e-conference and the internet helpline, include the Hec-Res, Hec-HMS, SWIM, Mike Info Works, ISIS and HBV. Schilling (2002) points out that, today, there are major data gathering, software and hardware breakthroughs which are helping to improve the dialogue among water professionals and the public they serve. These are helping to increase the water literacy of everyone. Schilling (2002) also points out that it is now possible to jointly and cheaply create sophisticated models with high validity in real time with professional and non-professional stakeholders, creating algorithms that are jointly owned by the stakeholders. This helps parties to create shared visions, and creates a cognitive map of alternatives in situations where parties are primarily disposed to claim value as opposed to creating value. McKinney *et al.* (1999) point out that the future direction for modelling will lie in GIS-based decision support systems that integrate economic, agronomic, institutional, and hydrologic components.

Chapter 2

Water resources planning and management

2.1 Water resources planning

Planning can be described as the function of selecting an institution or enterprise's objectives and establishing the politics, procedures, and programs necessary to achieve them (Kerzner, 1992). Planning is an art, a science, and an exercise in politics that involves application of common sense, experience, systematic methods, ingenuity, listening skills, ability to co-ordinate, making compromises and avoiding mistakes (Heun, 1998).

In water resources, planning is conducted to different degrees of detail for different purposes (Heun, 1998). Heun (1998) gave a break down of planning into three levels as follows:

- National and Regional Master Planning.
  Planning at this level is designed to:
  - Draw up an inventory of water-related problems and the needs of the people for the conservation and utilisation of water resources for the region. The region can be a single nation or a group of nations.
  - Express general guidelines and principles for solutions of identified problems and needs.
  - Identify specific regions with complex problems, where more detailed regional or river basin planning is needed (Crow, Lindquist and Wilson, 1995).
- River Basin planning
  Complex long-range problems that were identified in regional master plans are resolved at this planning level. River basin planning addresses needs, resource availability and potential for development of the water resources of specific basin. The responsible agencies identify problems and recommend action plans and

programs to be implemented in terms of well-defined projects. Projects are sized, and then the associated impacts, benefits and costs are determined (Heun, 1998; World Bank, 1993)

- Project Planning

  Solutions mentioned in regional or river basin planning are worked out in even finer detail. Alternative projects or programs are formulated and evaluated to determine the feasibility of solving the problem in a manner consistent with the guidelines contained in long-range plans. Planning in a project environment may be described as establishing a predetermined course of action with a forecasted environment (Kerzner, 1992). In project planning designs, cost estimates and estimates of impacts and benefits are addressed in detail. Project planning results in a specific course of action being recommended.

The core of planning exercises in water resources management is an analysis of the water resources system (WRS) (consisting of the natural, infrastructure and institutional subsystem), the socio-economic system and the environmental system. The WRS can be viewed as a source of goods and services (or products), and as a set of constraints to the other two systems. The management strategy (project), often in the form of a defined water resource project, aims to influence the level and availability of these goods and services (in quantitative and qualitative terms). The effects of the strategy are called product outputs, which may either be outputs that are aimed for or products that are not aimed for (non-products). Both types of products can have direct and indirect effects on the state of the socio-economic or environmental system. The management strategy requires inputs such as resources (land, water, capital) (Heun, 1998). Figure 2.1 illustrates the core components of planning as explained in this paragraph.

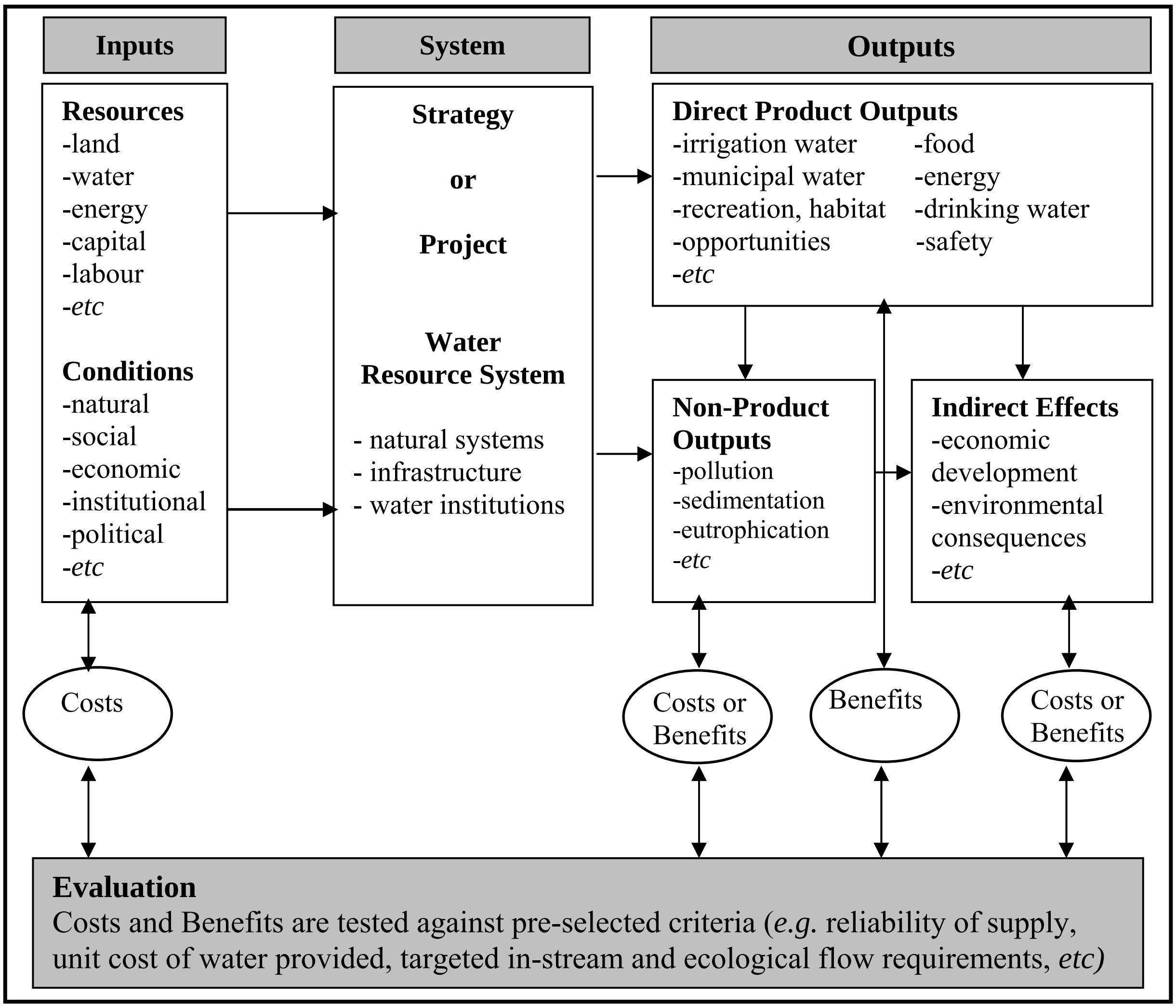


Figure 2.1 **The core components of water resources planning. (Based on original concept by Heun, 1998).**

2.2 Planning objectives in water resources

The objectives of water resources planning are characterised by a number of issues that include: (1) the scope of the water resources problem, (2) the level at which the problem is to be handled, and (3) the resources available to analyse the problem and develop solutions. As an example, the water problem in a particular irrigation project could be long dry seasons for which the main objective would be to develop a dam or dams that can release sufficient water throughout the dry season. This irrigation problem is not likely to be handled at a global level but probably within a catchment area grouping of water users or as a national project.

Lloyd and Berthelot (1992) noted that objectives have to be both realistic and achievable. A number of issues directly influence the objectives of planning in WRM. Some of the most important issues are:

- Global trends in the water sector,
- Water legislation and policies,
- Institutional frameworks in the water sector,
- Involvement of stakeholders in water resources management,
- Historical circumstances that affect the water sector,
- Governance systems in relation to WRM,
- International treaties and protocols in the water sector, and
- All water stakeholders within a water basin, including neighbouring countries where appropriate.

The national water resource strategy in South Africa provides a firm framework for the protection, use, development, conservation, management and control of water resources for the country as a whole. It also provides the framework within which water will be managed at regional or catchment level, in defined water management areas (Republic of South Africa, 1998).

Basson (1988) pointed out the technical objectives of water resources planning in South Africa. He noted that the following two objectives are at the top of the list:

- The need to maximise the reliability of water supply to the total integrated system
- The minimisation of the total cost of the water supply to the national economy.

The philosophy of IWRM, a global trend that has characterised most recent water management legislation, gives a comprehensive picture of objectives in planning in the water sector and takes account of:

- All components of the hydrological cycle,
- All sector interests and stakeholders,
- The spatial and temporal variations of the resources and demands,
- Relevant policy frameworks (national objectives and constraints),
- The national institutional levels, and

- Water legislation and governance.

Acreman (1998) summarises integrated water resources management as a central principle of managing water for the people and the environment simultaneously, and views the two as profoundly inter-linked. Acreman (1998) further points to South Africa's water policy's ninth principle as enshrining the idea of managing water for the people and the environment. The ninth principle says: "the quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved, so that the human use of the water does not individually or cumulatively compromise the long-term sustainability of aquatic and associated ecosystems."

The planning of the IWRM aspects as mentioned above is well illustrated in the use of the term "sustainable planning", where sustainable planning refers to: identifying demands and making the best decisions to meet them through a procedure that is simultaneously technical, political and a permanent process (Acreman, 1998). In the NWA, the need for an integrated approach to water management is noted at both national and catchment levels. The NWA (Republic of South Africa, 1998) in its preamble states the requirement to recognise the need for integrated management of all aspects of water resources. In Chapter 2 (1)(6)(*l*) of the National Water Act, a key objective, important to integrated planning at catchment level, is stated as follows: to promote the management of catchments within a water management area in a holistic and integrated manner.

In South Africa water resources planning should aim to achieve the principles of sustainability in each water catchment (Republic of South Africa, 1998; DWAF, 1997d). Merrett (1997) points out that "sustainable" in its current sense was first applied in reference to a sustainable society. Merrett (1997) further asserts that in the mid nineteen nineties, conferences and workshops on water and sustainability were marred by confusion over the use of this term, as some authors and speakers attached the adjective "sustainability" to "development" while other attached it to "environment". Sustainability as an objective or goal is seen as being praiseworthy, each writer or speaker hooks it to the noun that expresses the activity or entity that person most values. Merrett (1997) brought together the idea of sustainable development in the Brundtland definition and the idea of a sustainable society to come out with the following generic definition: "a sustainable society is one in which, for the indefinite future, human communities sustain and regenerate the species and habitats of the natural world, sustain and rehabilitate the quality of natural and built environments, sustain the global ecosystem's power to provide life-support services, and sustain and transform society's economic capacity to meet the material and cultural needs of all its people.”

A broader look at IWRM will show that although the ideas followed by different countries are the same, different countries have to some extent given different perspectives of this philosophy to make it more appropriate to the context of their circumstances, so as to include the existing legislation, socio-economic issues and political frameworks.

Some interesting aspects of IWRM that are noticeable in the literature from different countries are include:

(1) In Sao-Paulo, IWRM has also meant the recognition of water as a public asset, whose use has to be paid for in order to meet satisfactory standards for current users and for future generations (Porto, 2001).

(2) In India, an initiative called the "Four Waters" concept for IWRM is applied. The "Four Waters" concept provides a scientific approach to develop a watershed using rainwater, soil moisture, groundwater and surface water to derive the maximum benefit. The "Four Waters" project funded by the Government of India aims at arresting the present trend of year on year groundwater depletion through a number of large scale "watershed activities" (Hanumantha Rao, 1996). These "watershed activities" include:

- Producing two crops over the largest possible area of a watershed with a minimum of 20 000 ha per watershed,
- Developing groundwater recharge works,
- Growing forage cover crops to serve as mulch cover between crop harvests,
- Developing sub-surface dams, and
- Implementing water spreading techniques such as installation of hundreds of mini percolation tanks to spread the water within the boundaries of the selected 20 000 ha.

(3) In South Africa a very comprehensive approach has been taken, at least in the legislation as called for in the White Paper on National Water policy's 28 principles and objectives (DWAF, 1997d), which led to the National Water Act (Republic of South Africa, 1998). An item of particular relevance to IWRM is principle 18, which identifies the interrelationship between land and the water cycle and looks at co-ordinating land use management with management of water.

Four key concepts embodied in sustainable development are highlighted within a South African context in the national water policy (DWAF, 1997d). These concepts are:

- The need to take into consideration the needs of present and future generations
- The acceptance of rational limits placed upon the level of use and exploitation of natural resources, on the grounds that this is the only way to protect the capability of the resource for use and exploitation in the long-term;
- The role of equity principles in the allocation of rights and obligations, which also imply that the access to, and use of a resource, made by one user must take into account the needs of other users; and
- The need to ensure that environmental considerations are integrated into economic and other development plans, and that development needs are taken into account in setting environmental objectives.

The idea of a sustainable environment in the National Water Act (Republic of South Africa, 1998) calls for the following resource directed measures (RDMs) to protect water resources (Wright and Xu, 2000):

- Resource classification;
- Setting of the reserve; and
- Setting of resource quality objectives (RQOs).

Objectives in planning can be grouped according to five physical classes or spatial scales. Table 2.1 looks at five levels in planning objectives according to the five groupings.

Table 2.1 The water management problem at various levels.

Physical Units or Level (Spatial Scale)	**Important water related problems and issues**	**Advisory groups, Decision-Makers and Implementation Agents**	**Relative Ease of Implementing IWRM at this level**
1) World	-Greenhouse effects -Climatic changes -Increasing water demand -Virtual water transfers -Threats of water wars -International Legislation	-International Organisations *e.g.* IUCN, WHO, ICOLD -Symposiums and International Forums, *e.g.* Lome convention -International Courts	Almost Impossible
2) Region *e.g.* SADC, European Union (EU)	-International Waters and Legislation -Water quality control -large projects *e.g.* Lesotho Highlands Water Project -Standards of practice	-Regional Organisations and Institutions *e.g.* SADC, EU -Internationals tribunal and courts	Very Difficult
3) Country	-Legislation -Institutions -Large projects -Neighbouring countries -Pollution control -Resource sustainability assessments	-Government Departments -Water Engineering Institutions -Research Organisations - Stakeholder groupings	Moderately Difficult
4) Basin and Catchment	-Implementation of Legislative tools -Demand points and ecology -Large and Small projects -Pollution	-Government Provincial or Regional Departments -Catchment councils -Town and provincial councils -Private establishments and landowners	Easy
5) Rivers and Tributaries	-Flow Characteristics -Demand points and other users (nature) -Pollution monitoring and control -Storage facilities -Water loss: seepage and evaporation -Water projects	-Town and Provincial Councils -Water User groups -Government representatives -Individual researchers -Pollution Control Officers -Private firms -Individual water users	Relatively the easiest for implementing IWRM

Table 2.1 gives a listing of issues and problems considered at different physical levels and the organisations and agents that can handle these issues as advisers, decision-makers or implementers. It can be seen that there are overlaps in many respects but the table tries to give positions of the physical groupings where impacts or emphasis of the problem or issue is greatest. A column expressing the relative level of ease of implementing IWRM is included in Table 2.1 where the author points out that it is easiest for the smallest spatial level to implement IWRM, or at least come to a position where stakeholders decide that they have implemented IWRM successfully. It is however important to note that the measurement of success in implementing IWRM is relative, such that there are no known cases where all available literature and all stakeholders of a defined level such as a water catchment, agreed that IWRM had been successfully achieved. In many cases success in IWRM refers to particular objectives such as meeting targeted ecological flows, reducing industrial pollution, minimising water treatment costs and controlling the effects of floods and droughts.

In each of the five physical units or spatial levels mentioned in Table 2.1, and for the many units in each level, such as the several rivers or basins, a planning process should identify areas of interest and sources of problems, then attach priorities to goals to be met such as where investments should be channelled in each area, the sources and extent of the investment, time frames of project implementation, and expected system responses to the activities at each level. It is also critically important to define responsibilities and accountabilities for implementation to avoid possible project failures that result from ambiguities in the allocation of activities and functions to specific implementers.

Winpenny (1994) focused on solving water problems through managing water as an economic good. In his perspective water exists in an environment that can best be regulated on supply and demand ideals. Winpenny (1994) stressed that "water should be used 'optimally', which should be achieved when the marginal unit of water for each user has the same national value." In defining the solution to the water problem, he ends up pointing to the use of water cost and pricing structures to solve the water problem. Another perspective, that of Wolff (2000), is that the need for water, whether supported by ability to purchase or not, should be put in the forefront when making decisions on water usage. Reporting on his research in the Jordan River basin, Wolff (2000), noted that the problem of water needs in this area is an extremely pressing matter that goes beyond physical country borders. Wolff (2000) pointed out that the traditional approach that the UN and others involved in the attempts to resolve water conflicts in this area, where they use physical country borders to regulate water management and utilisation, will not solve the present problems. Wolff (2000) advised that water needs problems go beyond country borders and if nothing is done, armed conflicts are very likely to occur in future as people seek to satisfy their water need.

2.3 The planning process in water resources management projects where models are used

In conventional water resources planning, models are used as analytical tools where their use may be:

(a) To illustrate a situation;
(b) To simulate a process and derive possible outcomes of different choices or options; and
(c) To give probabilistic statements and time dimensions of processes and outcomes.

Most of the elements contained in the planning process are complicated in their own right and a range of types of models can be used to simulate these. A typical modelling approach in water resources planning is illustrated in Figure 2.2 below, showing areas where models can be used. As shown in Figure 2.2, planning relies on inputs from several organisational units that may be very large entities on their own, producing vast amounts of information. The information required in the planning of water resources management requires substantial investments in the storage and processing of information (Walmsley *et al.*, 2001; Chapter 14 of the NWA (Republic of South Africa, 1998).

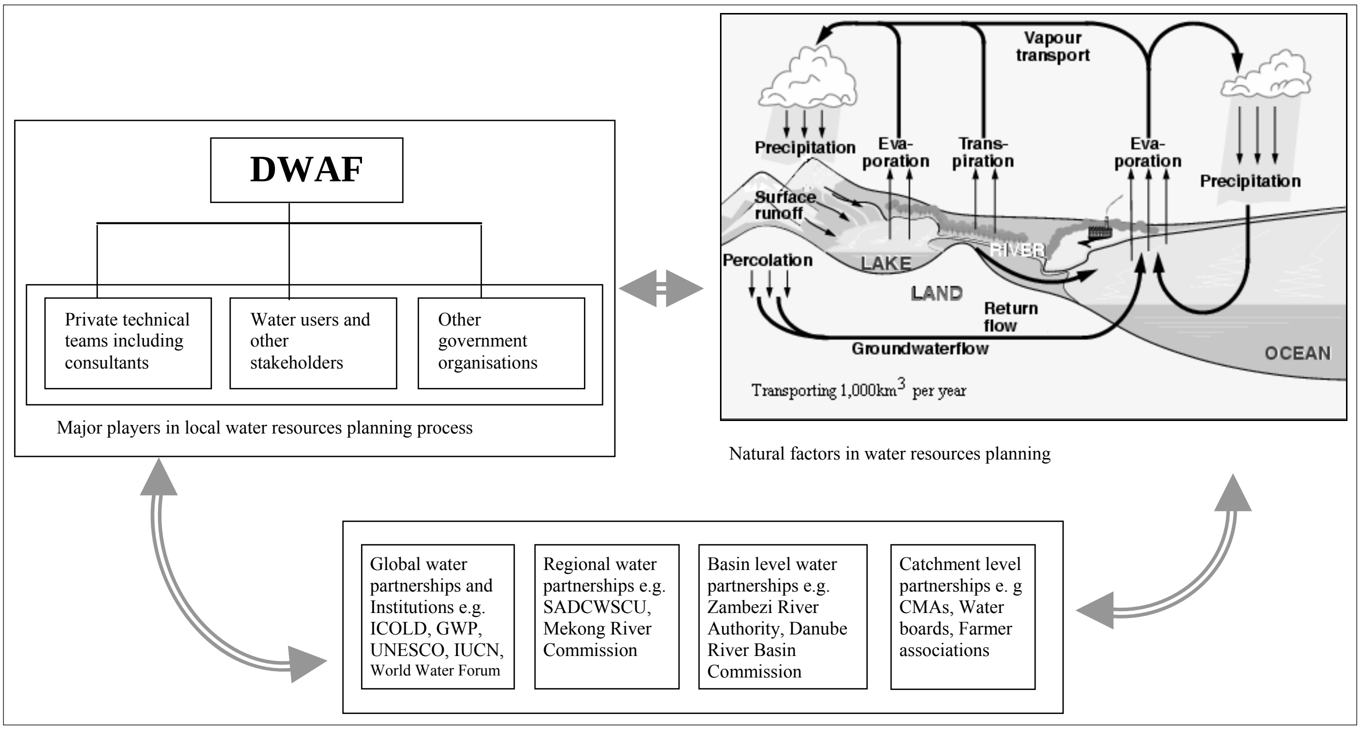


Figure 2.2 **Water resources planning components at various levels (The hydrological cycle diagram was adapted from Bengtsson, 1999).**

The planning process, whether models are used or not, should rely on multi-criteria analysis processes, where the various implications of proposals and recommendations are assessed using different units to provide "scores" for each criteria (Heun, 1998). The use of models and computers forces this process to become the core of the planning process, giving outputs in formats that are directly useful to decision-makers. Multi-criteria analysis, also called multiple objective analysis involves the use of scoring systems to score the performance of alternative strategies. Typical sequential steps in multi-criteria analysis involve the following (Heun, 1998):

- Determining the score for each criterion. Actual scores can be in "%" units for water shortage, "$" terms for investments, million m^3 for amounts of water stored, and even a simple "Yes" answer to indicate acceptance by the community.
- Determining the standardised scores. This involves normalising or reducing the units of each criteria to a similar unit. A number of methods are used in standardisation; two interesting methods include:
    - the scores for each criterion are divided by the sum of all the scores; the standardised scores should then add up to one.

  - the individual scores are divided by the maximum score: the score of the best strategy for that criterion; the best strategy score is then one and the rest of the scores will be less than one.
- Determining the weights for the criteria. The relative weight will show the importance that the decision-makers attach to each criteria.
- Selecting an arithmetic technique. Methods used can be the weighted sum method or the pair-wise comparison technique
- Presenting the results of ranking procedures to stakeholders and decision-makers
- Performing a sensitivity analysis. A sensitivity analysis will determine the extent of any effects that each criterion has on the obtained results, such that decision-makers and stakeholders will identify the project benefits and costs that are not sensitive, fairly sensitive and very sensitive to the different criteria.

In Figure 2.2, the water resources planning process is defined into three main elements:

- The local level; this being the planning processes within the country or river basin,
- The international level, which has major implications on what happens in individual countries, and
- The third element consists of the natural factors such as the water cycle which influences all planning processes.

From a computer solution development perspective, planning can also be viewed using three stages adopted from Eric (1999):

(a) The conceptual plans: This involves expanding the underlying concepts of water management including, legislation, institutional frameworks and the different policies that seek to solve the major problems that people face such as water shortages, flood disasters, poor water distribution and water pollution issues.

(b) The logical plans: In this planning level, the decision-makers, solution implementers, water users and other stakeholders come together to develop logical solutions to the problems. In their plans, they seek to capture all the concepts developed over time through practice, legislation and borrowed from other experiences within and outside the water sector, to give a basis to those practical solutions that could best suit their preferred state of the solution.

(c) The physical plans: The plans will seek to address exactly how to practically implement solutions to the problems, as outlined from the conceptual plans, using the logic already developed in the logical plans. At this level a tangible solution is the preferred output. As an example, the planning of a rural household borehole will be in such detail as to deal with the borehole siting, determining the water availability characteristics, such as quantity, quality and water level, how this borehole will be drilled, equipped and maintained, and who will implement each task.

Throughout the three stages mentioned above, the continued life of a project requires that responsibilities and accountabilities are clearly defined. This should clearly define who does what and when in the water resources project to avoid situations where a project continues to be utilised without maintenance until it is non-functional and then is forgotten or abandoned because no-one is prepared to take ownership and responsibility.

2.4 Water quality, quantity and spatial representation in water resources planning

Ideally, a surface water resource management plan should address both water quality and quantity issues in their temporal and spatial senses. While most water quantity models often have little to do with the quality of water, water quality models are usually modelled with water quantity modules as their base. The quantity and quality of water are not static processes, and to a large extent their variations are often unpredictably distributed in time and space. The structure of models and sub-models used in water resources planning should include a time and spatial reference such as a Geographical Information System to account for the spatial nature of the water management problem in terms of their quantity and quality.

Increasingly, water quality simulation capability is a standard feature of river basin models. Early water quality models were dimensionless, with assumptions of complete mixing, and only contained time-dependent variations of relatively straightforward water quality variables. The main variables considered were usually water temperature, dissolved oxygen (DO), and biochemical oxygen demand (BOD). More recently, fully three-dimensional, time-dependent models incorporating many realistic processes affecting water quality have appeared. However there are still major challenges to develop integrated water resources management and planning models with water quality components in a single holistic package. The tendency is to use a compartment or sequential approach where model component connections occur through the transfer of output data McKinney *et al.* (1999).

2.5 The planning model and its position in water resources decision making

Water resources modelling aims to obtain or derive the best and most up to date information from a water catchment or other water system, to help decision-makers to make the best possible decision regarding water utilisation and management.

There are two basic types of approaches used in planning models (Loucks, Stedinger and Haith, 1981):

(1) Simulation
(2) Optimisation

- Simulation relies on trial and error to identify solutions that are as near optimal as possible. The value of each decision variable is set and the resulting objective values are evaluated. The difficulty is that there is often a large number of feasible solutions or plans such that after simulation the decision-maker will not have a ready answer to a water problem, and this calls for subsequent optimisation. Simulation methods are able to solve water resources systems planning problems with non-linear relationships and constraints using mathematical procedures based on calculus and algebra.
- Optimisation procedures can be constructed to efficiently derive an approximation to the real problem, and may identify plans that will produce a solution that is close to the perceived optimum. Constrained optimisation algorithms include a diverse set of techniques that use calculus and matrix algebra.

An approach to modelling using ideas of dynamic multi-criteria analysis has been well presented for a very dry area by Al-Kloub and Al-Shemeri (1996), using a water management planning case study in Jordan. In their study, they identified and implemented a planning process using six steps, as described below.

Step 1: Identification of the problem and objectives of the water sector. This process involved understanding and defining the core problem (cause-effects relationships). The hierarchy of national objectives was broken down into lower level objectives to derive logical problem trees and objective trees.

Step 2: Selection and testing of the fundamental objectives, specifications of attributes and criterion weights through organised brainstorming workshops.

Step 3: Selection and development of projects, and the identification and quantification of constraints. At this stage, the options arising from the brainstorming workshops were surveyed to identify the best options. In their study, Al-Kloub and Al-Shemeri (1996) derived five groups of options for the water planning case study, that is: technical, regional, managerial, pricing and regulatory.

Step 4: Ranking and selection of projects
At this stage, complete ranking of all actions for water resources planning from step 3 was done. Sensitivity analysis was achieved through varying the weights of the criteria and observing the changes in the ranking of the actions. In their study Al-Kloub and Al-Shemeri (1996) used a method they called PROMETHENE, (Preference Ranking Organisation METHod for ENrichment Evaluation). Several other software-driven methods can be obtained on the market or developed for particular areas such as the customised systems models being used in South Africa.

Step 5: Measuring the water sector strategy performance
Al-Kloub and Al-Shemeri (1996) advised that the productivity of selected strategies in the catchment could be used as a performance measure to monitor changes in efficiency, effectiveness and quality. In their case study they used an interactive, constantly monitored, computerised evaluation of the strategy using the Multi-Criteria Performance

/Productivity Measurement Technique (MCP/PMT) method. This technique linked measurement and improvement directly to the needs of the customers.

Step 6: Improving the quality of planning of projects

In the planning case study in Jordan, an Object Oriented approach was used to develop the planning process. Wallis (1993) analysed the power and ease of use of Object Oriented approaches, from the physical project level to the actual software development process, and recommended this approach as one of the keys to the future of water resources modelling.

In South Africa a number of models have been developed to assist decision-makers in water resources systems planning. The most important models for surface water resources planning include:

- Pitman model
- ACRU Model
- Water Resources Yield Model (WRYM)
- Water Resources Planning Model (WRPM)
- Water Resources Simulation Model (WRSM2000)
- Water Situation Assessment Model (WSAM)

The Pitman Model: Pitman (1973) developed a rainfall-runoff simulation model which was subsequently referred to as the Pitman Model. The model was developed to simulate monthly hydrographs of river flows on the basis of available meteorological data and catchment parameters that could be derived readily from catchment maps. The model was developed to meet the circumstances that are often encountered in the South African situation, such as the absence of very fine details of hydrological data (Pitman, 1973). In addition the availability of hydrological records in South Africa is very variable, such that a number of areas where water resources assessments are required have no suitable recorded data to use in the assessments.

The ACRU Model: this is a physical conceptual model that integrates the various water budgets and runoff producing components of the terrestrial hydrological system with risk analysis. The ACRU model can be applied in design hydrology, crop yield modelling, irrigation water demand/supply, water resources assessment, and resolving conflicting demands on water resources. A very important aspect of the ACRU model is that it uses daily time steps, such that it requires inputs of daily climatic data (Dent, Smithers, Lynch and Schulze, 1995)

The WRYM: is the first model to be used in any analysis that involves the WRPM. It is used to assess the long-term yield capabilities of a water resources system for a given operating policy. It is used to analyse water resources systems at constant development levels, that is the system demands remain constant throughout the simulation period (BKS, 1986). This model is the preferred tool for all Catchment Yield analysis projects carried out for DWAF.

The Water Resources Planning Model: is a more complex model than the WRYM, and was developed to carry out detailed operation runs. The model is capable of modelling demands that increase with time as well as changing system configurations. It can be used both as a planning tool to assess the likely implementation dates of new schemes or resources, and also as an operational tool for the month to month operation of a system. Before the WRPM can be used, it is first important to undertake rigorous systems analysis using the WRYM. Such an analysis forms the first phase of any major system analysis and it is time consuming (BKS, 1986; McKenzie and Marè, 1998). A very important aspect of this planning model is the use of the Out-Of-Kilter network solver as the basic element (algorithm). The model is linked to an ARMA(1,1) multi-site stochastic streamflow generation package, specifically developed to reliably represent the highly skewed and variable streamflow conditions typical of the semi-arid South African climate (Basson, 1988). In DWAF, the WRPM is the tool of choice for all national planning analysis in water resources.(Van Vuuren, Van Rooyen, Fouchè and Haarhoff, 2001)

The Water Resources Simulation Model: has a modular construction where a catchment is simulated with four different types of modules linked by means of routes. The routes in the model represents the lines along which water flows such as river reaches (Pitman and Kakebeeke,1993), and relies on the rainfall-runoff ideas established by Pitman (1973). The main outputs in this model are simulated flow data that are used in some cases as the input to the WRYM and the WRPM models.

The Water Situation Assessment Model: this DSS tool for reconnaissance planning was developed in South Africa to assist in meeting the objectives of the National Water Act (Republic of South Africa, 1998), which requires the development of a National water resources strategy to ensure sustainable and equitable use of resources. The WSAM accommodates hydrologic variability by means of dimensionless storage draft frequency curves (expressed as a percentage of mean runoff) derived from a thousand years of stochastic records which are based on simulated natural flows for quaternary catchments. In the model, different curves are produced for different levels of assurance of supply. Only the parameters describing the curves are used in the model. The model depicts the status of balance between available water resources and demands, relative to pre-set conditions and growth scenarios for future conditions.

The WSAM, which is currently under development, is GIS enabled and supported by a comprehensive database of spatial water-related information, including stream flow reduction activities, natural and man-induced inflows, water storage systems, as well as natural and man-made water flow facilities (DWAF, 2000). The WSAM model provides water use projections at quaternary level, based on different economic and demographic development patterns. The projections currently covered by the model are up to the year 2005.

2.6 Surface water resources models and the modelling problem

Surface water resources models provide a way of transferring knowledge obtained from a measured or study area, to an area where objective hydrological decisions and information are needed (Schulze, 1998). Water resources models utilise mathematical techniques and theories to examine water catchment behaviour or responses. The methods used in models vary from simple empirical relationships to complex multidimensional conceptual representations of the catchment in a dynamic state (Mulder and Kelbe, 1991). All these models are driven by variables that are regulated by the model parameters. The parameters generally represent features of the system that are usually considered invariant within the constraints of the simulation period. Parameters are also defined as the dimensionless weighting coefficients used in the model to reproduce hydrological responses (Schulze, 1998).

In the development and application of water resources models there is a general belief that the more complex the model, the closer it approaches reality. This argument is valid to some extent because of the complex nature of hydrological processes (Dooge, 1986), which are the main components of water resources models. The hydrological processes have non-linear relationships, which are further complicated in modelling by restrictions and shortcomings in several modelling processes and the resources available to the modellers (Mulder and Kelbe, 1991). Restrictions in the modelling processes in areas such as the ability of computer code to simulate a catchment, the model developer's understanding of the processes to simulate, and how they work in nature, mean that many processes in the model are gross simplifications of the actual physical process. Increasing the sophistication and model complexity, however, may be severely restricted by the suitability of parameter representativeness as well as the number of parameters required to describe all the relevant processes adequately (Beven, 1989). Consequently, the applications are frequently restricted to lumped (2-D) numerical models which cannot account for any spatial heterogeneity in the catchment processes except through partitioning of the catchment into increasingly smaller homogenous units (Mulder and Kelbe, 1991). All the models that the author has used including those mentioned in Section 2.5, fall in the 2-D category, and do not include spatial heterogeneity.

In essence a hydrological model simulates the complexities of the terrestrial hydrological system. Dooge (1986) describes a terrestrial hydrological system as a "complex" system with some "degree of organisation". He points out that, in models, developers can only abstract certain parts of the complex system in order to understand and predict the behaviour of those parts of the system. Therefore, models can only attempt to represent the actual physical conditions of the catchment with a limited degree of accuracy. Dent (2000) warns model users and decision-makers who receive the modelled results against simplistic models, he says " complexity holds the promise of functionality and simplicity holds dangers". Dent (2000) also noted that simple models are useful because they provide an introduction for beginners in modelling to learn the art, but they are a danger if used beyond their bounds; a fact which he claims often goes unnoticed.

Surface water models attempt to describe three basic processes within any catchment (Schulze, 1998). These are:

- Storage of water (within the soil, vegetation, aquifers and water bodies)
- Loss of water from storage (by evaporation, percolation and lateral flows)
- Routing of water (over the surface, through the soil and aquifers, and through channels, reservoirs and wetlands).

The main objective of hydrological modelling is to gain an understanding of the hydrological system in order to provide reliable information for managing water resources in a sustained manner, to increase human welfare and protect the environment (Schulze, 1998). Variations on this theme include the use of hydrological models in the following types of applications:

- Making efficient and cost-effective quantitative estimates of water-related variables at ungauged locations under varying climatic and land use conditions.
- Making decisions relating to the planning, design, operation and management of water related structures such as dams, waterways and bridges
- As a means of communicating hydrological information to the layman, the non-hydrological technocrat responsible for planning environmental resources, and the decision-maker (for example, a politician) who may not have appropriate technical training to understand or appreciate the complexity and ramifications of the decisions they are making.
- Models may be used to provide strategic and technical support to a research programme by motivating researchers, providing frameworks for hypothesis testing, assisting in formulation of ideas, and integrating the scientific findings (Grayson, Moore and McMahon, 1992)
- Hydrological models can generate useful information from limited data (Schulze, 1998)

Grayson *et al*. (1992) mentioned the need to be cautious when using models and applying the results obtained from models. Notes of caution include the following:

- Models cannot substitute or compensate for a lack of hydrological knowledge or incomplete understanding of the natural hydrological system (Grayson *et al*., 1992)

- Models do not create new data or facts; these can only be provided from observation and experimentation (Schulze, 1998)
- Models should therefore never be compared against other models when assessing their accuracy, only against observations (Schulze, 1998)
- Models are tools that can only be used as a means to an end and should not be seen as an end in themselves (Pereira, 1984)
- It is a myth that models are objective, in essence they are a sequence of assumptions, each of which is subjective (Dent, 2001). Models have a cultural background because they are a product of human thought working within a sequence of assumptions (Dent, 2000).
- More information is not necessarily the solution to the water manager's problem (Sterman, 1989; Senge, Robert, Ross, Smith and Kleiner, 1995; Dent, 2001). Sterman (1989) points out that research results directly contradict the assumption that all that managers need for better decision making is more information. Most decision-makers often "filter" their information through non-systematic mental models, construing symptoms as causes and sometimes reacting in ways that make problems worse rather than better (Sterman, 1989). Increased information is, however, viewed as the key to enhancing learning, which positively improves the decision-maker's ability to interpret information.
- Not every problem in hydrology requires the use of a simulation model. Many problems can be solved conceptually, as a mental exercise, or by a round table discussion between experienced practitioners.

On a catchment basis, IWRM is broad and complex such that modellers are generally of the opinion that no single model can be used to the exclusion of all others (Dent, 2000). The idea of modelling one aspect of the water resources system which will be a source of concern or a problem at that time is viewed as a limited approach in the context of the National Water Act, that calls for an integrated approach in water management. Dent (2000) points out the need for a system that facilitates interoperability between time-dependent data and information, which are used and produced by the different modellers in the integrated water system. He suggests that this will be in the form of an overall "operating system" or nested sequence of systems that enable reasonably flexible linking of the core functions of individual models. Examples of similar integrated systems that have been applied in other sectors are given as the Petrotechnical Open Software Corporation (POSC) developed for the European Petro-technical Industry and the R/3 integrated software suite developed by the German developer SAP AG, which is being used in many manufacturing industries world-wide. The development of the systems in "Better Assessment Science Integrating Point and Non-Point Sources" (BASINS), a tool developed in the United States for the generation and analysis of model simulation scenarios for watersheds, is testimony to the usefulness of inter-operability in the water sector (Dent, 2000).

2.7 Social and economic factors in water resources modelling

The NWA promotes a holistic and integrated approach to water management and one of the main purposes of the Act is to facilitate social and economic development as well as socio-economic viability. Schilling (2002) pointed out that although IWRM is reasonably well understood as a concept, it lacks precise definition. At the same time, we hear that water must be valued better; that it is an economic as well as a public good. Modelling tools therefore have to be developed and used in such a way that they allow multi-criteria assessments of social and economic factors in addition to hydrological features. Schilling (2002) further expressed that due to the population growth, development needs, and most important, ecological integrity and service needs, the claims on water are growing and the mix of water use patterns is changing with time. These changing water use patterns mean that many water resources tools developed in the past are becoming less and less useful with time.

Talking of the South African case, Schreiner and van Koppen (2000) pointed out that the most tangible but analytically flawed implication of the statement that “water is an economic good,” is on the pricing of the capital and operational costs of infrastructure. Water pricing has been implemented as a blanket policy and has proven to have considerable cost to society in that water deprivation is aggravated and inequities are amplified. Pricing as a tool for water conservation and demand management is not about poor people having to give up the use of water, but saving water where it can be saved without negatively affecting beneficial use. Pape (2001) discussed a situation in the Hermanus Municipality where poor water consumers had their houses auctioned as the municipality enforced stringent measures to collect outstanding water use charges. According to Pape (2001), the Hermanus Municipality had a narrow vision and failed to address water socio-economic issues. Despite the critical importance of financial viability, water resources allocation, management and planning requires an interdisciplinary approach, integrating natural and social aspects (McKinney *et al.*, 1999).

Changes in the economic environment resulting in increased water demand along with evolution of societal attitude towards water resources have led to an escalation of local conflicts over water use and conservation (Giraud, Lanini, Rinaudo, Petit and Courtois, 2002). As a result, participatory approaches are promoted to design water management policies and establish institutions where such disputes can theoretically be discussed by stakeholders and solved or prevented through negotiation. Giraud *et al.* (2002) also noted that the success of these negotiations is enhanced by providing stakeholders with suitable interactive tools to investigate and compare the impact of various water management scenarios. Dinar (2001) explained that these interactive tools should utilise incentive-based measures for improving efficiency in resource use. He suggests the inclusion of the following economic measures in water resources management planning and management tools:

Pricing - Ideally pricing should be set for situations where maximum economic efficiency is attained when the price is set at the level where marginal costs equal marginal benefits.

Subsidies – The provision of subsidies will either be directly to users of water or for a water use technology.

Taxes – These will be designed to modify behaviour by encouraging particular water user groups or activities, and could be implemented in the form of preferential tax treatment to certain producers or residential consumers through tax credits, exemption or deductions, or through tax benefits provided to investors.

Quotas - The water quota system should aim to define the limit on water use or to establish how much to use, when, by whom, and for what purpose water can be augmented and used.

Ownership/ rights – The “Ownership” or ”water rights” should be used to refer to the right acquired by the user under government regulation or water law for the abstraction, diversion, use of water, establishment of water infrastructure, or accumulation of proceeds from water tariff collection.

McKinney *et al.* (1999) explained that it is only by considering all interactive components that optimal use from a socio-economic standpoint can be established in water resource management. With the growing scarcity of water and increasing competition for water across and between sectors, social and economic issues in water allocation are becoming increasingly important in river basin management. McKinney *et al.* (1999) identify the following economic concepts and issues that need to be examined through integrated socio-economic-hydrologic river basin modelling:

- Transaction costs,
- Agricultural productivity effects,
- Inter-sectoral water allocation,
- Environmental impacts and
- Property rights in water.

Typically, two approaches have been used to develop integrated socio-economic-hydrologic models: the compartment modelling approach, and the holistic approach. The compartment approach involves loose connections between different model components where only the output data are usually transferred between components. This approach can allow the individual components to be very complicated, but it is difficult to analyse due to the loose connections. In contrast, the holistic approach has one single unit where the components are tightly connected and information transfer is conducted endogenously. This approach requires the use of a unified dynamic programming approach and one single denominator or platform for the variables (Larsen, Mark, Jha and Das Gupta, 2004).

Chapter 3

Unique South African features in water resources modelling

3.1 Legislation and policies affecting water resources modelling

3.1.1 Implications of the NWA on water resources modelling

The national legal framework consisting of the National Acts, policies and regulations defines important boundaries in water resources management and planning models. The enactment of the NWA (Republic of South Africa, 1998) introduced new legal frameworks, which meant that water resources models developed or in use had to be updated or replaced accordingly. Important issues for water resources modelling in the NWA include the following:

- Revised definitions of water users,
- Water use prioritisation where the reserve and international obligations have the highest priority,
- New licensing processes which now incorporate revised water use definitions,
- Provisions for the development of integrated water management tools and national water information management systems,
- The establishment of Catchment Management Agencies (CMAs) to plan and manage water at WMA level.

Chapter 4, Part 1 of the NWA defines water use broadly to include: taking and storing water, activities that reduce stream flow, waste discharges and disposals, controlled activities (activities which impact detrimentally on a water resource), altering a watercourse, removing water found underground for certain purposes, and recreational use of water. In general, a water use must be licensed unless it is an existing lawful use, is permissible under a general authorisation, or if a responsible authority waives the need for a licence.

The NWA's principles of equity, efficiency, equality and sustainability have major implications for the rules that are set in water resources models. An elaborate tendency to incorporate efficient and beneficial use, sustainability and ways for redressing the results of past racial and gender discrimination (NWA, Section 27.1) are now preferred in all water resource management and planning processes including modelling.

Section 43 of the NWA provides for the compulsory licensing of water users, and in section 45, provisions are made for the scheduling of water allocations. Water users can dispute the prescribed allocations, so the tools used to determine them have to be very accurate, reliable and holistic. The water allocation schedules can only be prepared after meeting the water needs assigned to the water reserve and any relevant international obligations. These water allocations should not result in further deterioration of the quality of the water resource. Water resources modelling should therefore take into consideration the legal provisions contained in Sections 16 and 17 of the NWA, where classification of water resources systems and establishment of the reserve are handled.

Section 56 (4) of the NWA provides direction for modelling in cases where the water pricing strategy has to be accounted for. In this strategy, water pricing may differ depending on: geographical location of area, the water use category and the type of water user. Ideally water resources models must therefore allow for these pricing variations.

The NWA sets the basis for integrated water resources planning and management in South Africa. As a result many water resource modelling projects are now required to take an integrated and holistic approach. This requirement has been very obvious in drafting the terms of reference for the national water resources assessment project (WRC, 2003b). This project, which originally focussed on surface water resources, had to be redefined to include an integrated approach encompassing water quality, groundwater, ecological requirements, socio-economic issues and population demography.

3.1.2 Impact of policies and regulations on water resources modelling

The White Paper on Water Policy (DWAF, 1997d) was used as the basis for reviewing and reforming South African water law. The water legislation reforms resulted in the 1956 Water Act (South Africa, 1956) being replaced by the National Water Act of 1998 (Republic of South Africa, 1998).

One of the important purposes of the 1997 Water Policy was to outline the proposed institutional framework for water management functions. The 1997 policy also recognized that the law is the basis of our collective action as a society and must therefore underpin our public efforts to manage water resources. The policy defined different factors and rights which should be considered in relation to water. These included the following:

- The right to equality
- The rights to dignity and life
- Environmental rights
- Property rights
- The right of access to sufficient potable water

These rights, which must be represented in water resources management and planning tools, including models, have different definitions today from those that were used in the earlier South African water law, the 1956 Water Act (South Africa, 1956). All of these rights must be considered together as providing the environment in which water management practices and modelling tools should take place.

The principles and policy visions of the 1997 water policy seek to promote:

- Equity in access to water services
- Equity in access to water resources
- Equity in access to benefits from water resource use
- Optimum resource use and protection

- Environmental sustainability
- Social and economic benefit

These principles and visions embodied in the 1997 Water Policy have direct implications for water resources modelling objectives. Models that focus on a single point rather than taking a holistic approach to the water system cannot address the integrated approaches required by the NWA, that seek equity, efficiency, optimum use and sustainability. The new approach also emphasises the need to use spatial integration where simulations at each point are done in relation to all other connected points in the whole country, including connected catchments in neighbouring countries. Most water resources systems analysis networks do not adequately account for poorer settlements such as townships in an integrated approach with other water consumption points. Examples include the water resources planning studies carried out in the ORRS (DWAF, 1998a) and the Vaal River System Analysis (BKS, 1986) projects.

Water management at the smallest spatial and temporal resolution is guided by water regulations. These regulations provide the boundaries for most operational level modelling in the catchment as well as other high resolution water resources planning and management. The water management and planning tools expected to be used by the CMAs will rely on the correct interpretation of regulations and water operation rules. Continuous water release, supply, abstraction and storage at detailed time steps and very fine spatial resolution, need very accurate operation rules that will be set by the responsible catchment management agencies, water municipalities and other water user authorities.

3.1.3 Implications of southern Africa's regional water sharing

Integrated water resources management and catchment management seek to manage water in hydrological and ecological units. These units usually cut across administrative boundaries and, in many cases, country borders. Water resources planning, management and data collection are often adversely affected by having to cross administrative boundaries especially in the case of crossing country borders (UN, 2001). This requires water resources managers to deal with complex issues which include different administration, cultures, languages, legislation, data and water management tools. Transboundary water resources planning and management has to take into account a number of issues which include: political, legal, environmental, socio-economic, cultural, technical as well as other catchment related characteristics. All these characteristics, which are discussed below, present different constraints.

- **Legal issues**

Sections 102 to 108 of the NWA (Republic of South Africa, 1998) are dedicated to the management of international waters. The NWA seeks to promote peaceful cooperation with neighbouring countries in the management of all shared water resources. Transitional provisions were also made in the Act to ensure further support of existing international water management bodies such as the Trans-Caledon Tunnel Authority, the Komati Basin Water Authority, and the Vioolsdrift Noordoewer Joint Irrigation Authority. The transboundary water bodies set water management frameworks, handle international waters agreements and ensure that stakeholders adhere to these agreements. Section 45.2 of the NWA (Republic of South Africa, 1998) gives a high priority, second only to that accorded to the reserve, to the provision of water to meet international rights and obligations. All other water authorisations, allocations and licensing will only be made after the reserve and the international obligations have been met (Section 27 of the NWA) (Republic of South Africa, 1998).

- **Catchment characteristics in relation to neighbouring countries**

Cases of downstream water users failing to receive their fair share of water due to uncoordinated upstream catchment planning are a major concern in trans-boundary catchments. Typical examples include the Incomati, Umbeluzi and Maputo Basin shared between South Africa, Swaziland and Mozambique (White, 2001).

A number of initiatives to improve catchment data on international basins are underway. This includes the Southern African Development Community (SADC) surface water resources project (SADC, 2003a) and the Flood Early Warning System for southern Africa (Artan *et al*., 2002). Water resources models developed for use in trans-boundary catchments have to be adapted to the resources available in the different countries which are usually different in terms of detail, quality, availability and readiness for use. Hughes (1997) noted how complications in dealing with transboundary water resources modelling data can derail projects and increase project costs. Hughes (1997) experienced several challenges while putting together the data for monthly water resource modelling in southern African countries. In some countries such as Zambia the only way to secure data was through time consuming procedures that usually involved paying inflated unofficial prices. Lynch (2003) pointed out that his team's regional rainfall data collection and analysis project was faced with varying data formats including volumes of unprocessed hand-written records that required significant human resource inputs to enter data. Both Hughes (1997) and Lynch (2003) encountered many catchments with no rainfall and runoff gauges. The initial task in the modelling of trans-boundary water resources is to investigate the available data resources and identify the suitable modelling tools in terms of the resolution in time and space. While many developed countries and some developing countries are now targeting very small-scale resolutions extending to a few metres in the catchment, and less than hourly rainfall, and flow records using models such as MIKE SHE connected to DTMs (Collins and Campbell, 2003), this approach is difficult to pursue in most southern African countries where data resources are inadequate. Data availability is a major obstacle in high resolution water resources modelling and there are very limited initiatives to improve local data availability at uniformly detailed temporal and spatial scales.

- **Equipment, technology and modelling resources**

The water resources tools and technology used in southern African countries sharing the same water basins are different, and have little complimentarity in many respects. In addition, a general trend of maintaining minimal data recording facilities throughout southern Africa affects the availability and distribution of required data resources. As a result, projects such as real-time flood assessments have to rely on a variety of tools with different levels of accuracy such as satellites, Radio Detection and Ranging (RADAR) in some areas, physical gauges in others and aerial measurements where available. Projects spanning shared basins also need to include capacity building components. The SADC surface water assessment project (SADC, 2003a) is one such project that aims to develop some regional institutional capacities in water resources. The author also noticed that stakeholders had a tendency to resist country-specific approaches, including otherwise useful models brought in from other countries (SADC, 2003b). The processes followed and tools used in developing agreements and projects on transboundary waters have to deal with national differences with sensitivity as it can derail otherwise viable initiatives. International projects are known to take many years of negotiation before agreements are reached due to perceived differences. As an example the negotiations on the LHWP were initiated in 1954 while the signing of the Lesotho Highlands Water Project treaty took place many years later in October 1986 (DWAF, 1986).

- **Environmental, socio-economic and cultural issues**

Projects in trans-boundary catchments and river basins face major challenges in cases where socio-economic and cultural issues are different. This author witnessed a number of socio-economic challenges while working on hydrological assessment projects for the Incomati, Maputo and Umbeluzi River Basin. The projects involved, role players from Mozambique, South Africa, Swaziland and Sweden. The challenges faced related to the appreciation of methods used, different expectations by the teams from different countries, as well as limitations in communication due to language and cultural differences. Hydrological simulations were done using the Swedish Hydrologiska Byråns Vattenbalansavdelning (HBV) model (Lindstrom, Johansson, Persson, Gardelin, and Bergstrom, 1997), which was supported by Swedish International Development Agency (SIDA) funding. The South African Pitman model was utilised to generate runoff data in the basin catchments. The use of these tools was not readily acceptable especially in the Mozambique catchments as the tools and documentation were in English while most of the members of the Mozambique team were Portuguese speaking. The need to translate some of the HBV and Pitman model documentation into other languages such as Portuguese in this case became apparent. It is also important to note that some of the complications in transboundary water management are due to differences in the values attached to specific modelling approaches and outputs. As an example, Historical Firm Yield (BKS, 1986) is considered to be a very important catchment measurement parameter in South Africa, however this term has little significance to some international stakeholders where other terms to define water availability are used.

While water resources management aims for sustainability, a culture and perception that water should be freely available exists in most of South Africa. The Water Services Act (Republic of South Africa, 1997) states that it is the duty of consumers to pay reasonable charges for water supply services in accordance with the provisions in this Act. Despite this legal requirement, frequent community demonstrations against payment of rates for water provision are a common occurrence in most peri-urban settlements as well as low income residential areas. Water resources planners and managers have to allow for some flexibility in their plans and operations to handle community needs. The tools used for water operational planning and management should ideally incorporate solutions to the challenges posed by socio-economic and cultural issues.

3.2 Water resources stakeholders and institutions in water resources modelling

3.2.1 Water institutions

The NWA defines a “water management institution" as the state, a catchment management agency, a water user association, a body responsible for international water management, or any person who fulfils the functions of a water management institution in accordance with the Act. These institutions form an important building block of water resource management and planning. Water management institutions are tasked to plan, manage and implement the day to day water resources operations, from the smallest point of use such as the water tap, to large water use units such as urban settlements. The water resource modelling tools are there to support and provide information to decision makers in water management institutions. Institutions utilize the outputs of modelling tools to enforce water laws, regulations and policy requirements (Moriarty *et al., 2001).*

The institutions and their stakeholders should have mutually agreed methods of measurements and assessments in water management. Moriarty *et al.* (2001) pointed out the existence of wide-spread stakeholder disagreements on how to measure water use as required in South Africa’s NWA. Typical examples include the determination of water use by forestry for licensing and the process used to charge foresters. Proposed water use quantification and charging methods which involve the use of the ACRU model in conjunction with tabulations based on field measurements have continued to be contested by the forestry community who have cited that the methods were inadequately researched and are inaccurate because they were derived from case studies which were done in a few high rainfall catchments which do not represent the hydrological conditions of most other areas. Significant research including two new projects in the Water Research Commission (WRC, 2003a) have been initiated to develop more accurate and reliable methods which can be applied at any location in South Africa at different time and spatial scales.

In the NWA, water resources management at smaller scales such as field/plot level at daily time resolution as well as operational modelling such as managing the daily releases of a dam for a hydro power plant will be part of the CMAs' daily tasks. Some of the CMA activities where water resources modelling will be applied include the following:

- Implementation of catchment management strategies,
- Defining rules to regulate water use, within their zones of authority,
- Continuous water use monitoring,
- Recording, monitoring and storage of records on storage levels, water abstraction, water pollution and river flows,
- Developing long-term water plans for each WMA,
- Multi-criteria analysis of each WMA's water resources,
- Water resources development and maintenance plans, and
- Control, limit or prohibit use of water during periods of water shortage.

3.2.2 Water stakeholders

The presumption that science knows what is good for society is increasingly under challenge by the society. For example, Cribb (2003) pointed out that the public pressure is rising for democratisation of science. Involvement of society in water resources management projects is now expected to begin at project conception stages. Cribb (2003) further pointed out that there are two imperatives in water management. These are:

- Stakeholders need to know the necessity for IWRM, as well as the facts and the issues surrounding water availability and its quality over time.
- Stakeholders must have an equitable part in the dialogue over what is to be done.

Stakeholders in water resources modelling can be segmented as follows:

- Decision makers (Executives and board members of water institutions, politicians, water managers and water legislators)
- Technical specialists and advisors (scientists, engineers, town planners, researchers and model users)
- Model developers and users (computer technicians and researchers)
- Technical agents (laboratory technicians, field data collectors and GIS specialists)
- Water user groups (farmers associations, forestry commissions and industrialists)
- Lay public (water users in general)

Most technical stakeholders, including scientists, are narrowly focussed in terms of their concerns over water. The water policy framework on the other hand, exists in a multiple-issue and multiple-constituency world where the agenda is constantly changing and where environmental issues are amongst many competing for the attention of water resources managers (Oxley, Winder, McIntosh, Mulligan and Engelen, 2002). Oxley *et al*. (2002) also pointed out that researchers frequently refer to a rational ‘decision-maker’ as some autonomous individual located at some higher level in an administrative hierarchy. In reality, policy formulation and decision-making are complex processes involving many stakeholders and many different forms of knowledge, and it is difficult, if at all possible, to pinpoint the moment at which, or the people by which, a decision is arrived at. In most natural resource projects, communities who depend on these resources should ideally have the final say, which unfortunately is expressed very late in projects due to their lack of initial involvement (d'Aquino, 2002).

Different stakeholders often have other perceptions about possible solutions to problems and differences in opinion between stakeholder groups can lead to conflicts. A concept of integrating water resources management, socio-economic behaviour and hydrological functioning can be utilised in improving stakeholder involvement, decision making and solution development (Giraud *et al*., 2002). Giraud *et al*. (2002) developed an interactive simulation tool with the aim of closing the gaps between the levels of understanding of water resources management issues by practitioners and other groups of stakeholders. These stakeholder tools should ideally be used for the purposes of improving understanding rather than generating solutions. Giraud *et al*. (2002) reported that in France, only 3 out of 42 negotiated water management plans that utilised stakeholder tools for solution development succeeded in the period 1997 to 2001.

The NWA and many authors are gender sensitive, and distinguish all stakeholders in terms of gender in an effort to redress what is usually referred to as "gender marginalisation". Schreiner and van Koppen (2000), in similar sprit called for equitable participation by men and women, particularly by poor men and women in decision-making, not only with regard to the water supply schemes to their own villages, but in relation to broader resource allocation and planning within the catchment.

3.3 Hydrological processes in South Africa in relation to water resources modelling

The understanding of hydrology in water resources management and planning is handled through various spatial scales that range from point to global. At point scale and other high resolution scales, understanding of processes is usually the focus, while at larger scales such as global, the focus is on earth systems. The detailed understanding of the rainfall responses at very small scales such as hill slopes is key to the development of suitable parameters in water resources models and in the formulation of correct hydrological simulations. At these small scales, hydrological processes can be physically assessed to determine constituent building blocks of larger scale observed processes such as measured river flows or dam storage levels. To understand hydrological processes, rainfall, which is the main driver in most of South Africa's hydrology is partitioned into various components stormflow, baseflow, snowmelt, evaporation, interception, soil water storage and ground water recharge. Environmental factors such natural conditions and the impacts of anthropogenic pressures in reshaping hydrologic responses also need to be accounted for when addressing the implications of hydrological processes in water resources modelling. South Africa is characterised by a uniquely non-uniform climate that ranges from sub-tropical in the northern parts to temperate in the southern areas. Desert conditions prevail in large areas of the country where water provisions are based on ground water supplies or water transfers from wetter catchment areas. Anthropogenic impacts on hydrological processes in South Africa, such as those arising from human settlements, are also unique when compared to most of the countries involved with the development of available water resources models. In the case of settlements, informal settlements without provision of services are widespread throughout the country. These settlements have major influences on catchment hydrological responses and also impact on the water resources planning processes.

3.3.1 Rainfall

South Africa's average annual rainfall is 462 mm (Lynch, 2003), against a world average of 857 mm. Twenty-one per cent of the country has a total rainfall of less than 200 mm annually, 48 per cent has rainfall averages ranging from 200 mm to 600 mm, while only 31 per cent records more than 600 mm each year. In total, 65 per cent of the country has an annual rainfall of less than 500 mm which is usually regarded as the absolute minimum for successful dry-land farming.

Rainfall is the main source of water input into the hydrological cycle and therefore plays a crucial role in simulations. Rainfall data are obtained through measurements obtained with a variety of methods. The most common measuring method utilizes the standard rain gauge. Measurement by RADAR and satellite is also practised. While RADAR and satellite imaging for rainfall estimates are able to give real time, aerial estimates of rainfall data, the primary source of rainfall data is still provided by rain gauges (Gill, 2004) which give point rainfall data. Rainfall gauge distribution in South Africa is far from uniform, with dense gauge networks in high rainfall area such as coastal areas, Natal, Gauteng and Western Cape provinces, while thousands of square kilometres in dry areas do not have rainfall gauges. One hopes that, over time, the rain gauge network density will increase, since water resources modelling depends directly on continuous well-distributed rainfall recording points. Initiatives to develop new rain gauges tend to develop additional rain gauges to replace closed stations rather than increase the spatial gauge distribution (Lynch, 2003). As a result, areas with dry climates are likely to remain ungauged.

Rainfall recording in South Africa started at the Royal Observatory (Station 0020866 W) in Cape Town in 1850.The number of active rainfall stations increased from 1 in 1850 to 3841 in 1938 (Lynch, 2003). Thereafter, however, there has been a consistent decrease in the number of active gauges, as shown in Figure 3.1. Presently, there are fewer than 3000 active rainfall gauges in South Africa.

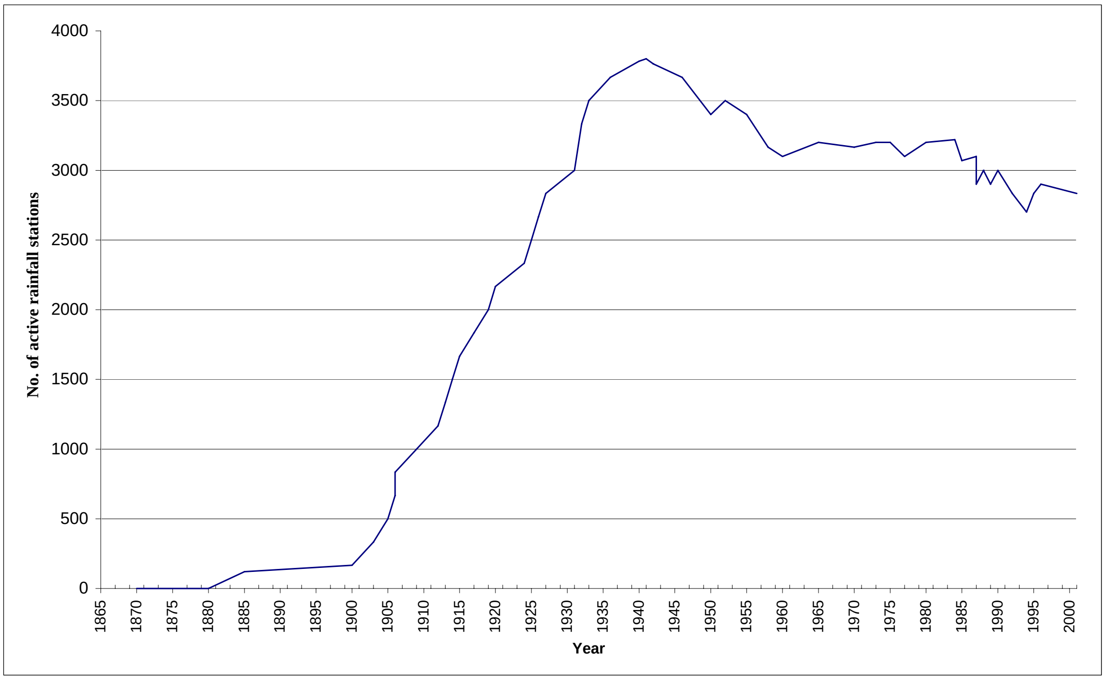


Figure 3.1 Number of active rainfall stations over time (Redrawn from Lynch, 2003).

Another rainfall measuring method that is increasing in popularity is the use of RADAR for aerial measurements. RADAR instruments measure rainfall by determining the time taken for a small pulse of electromagnetic energy to travel to a targeted area and return after reflection from the target (Clift, 1985). The intensity of precipitation falling upon the ground can be assessed regularly with accuracy at ranges of up to 100 kilometres in the sub-tropics and up to 150 km in tropical countries (Clift, 1985; Jewitt, Terblanche, Görgens and Mittermaier, 1998). Sources of errors in RADAR measurements have to be eliminated before the application of data. Known problems with RADAR rainfall measurements include:

- A "bright band effect" which affects rainfall estimates. The bright band manifests itself as a series of concentric annular rings on an accumulated rainfall field. The rings are usually the result of melting ice particles falling through the 0°C temperature level which are erroneously detected as rainfall events. The problem results in increased rainfall records. In a study of rainfall-runoff simulations on the Liebenbergsvlei catchment in South Africa during the heavy rains of February 1996, Jewitt *et al*. (1998) found that the rainfall records were occasionally overestimated by factors as high as 2 using the RADAR method.

- A "ground -clutter" effect resulting from abnormally high reflectivity values caused by topographical features such as mountain ranges result in overestimates of rainfall in mountainous areas (Jewitt *et al*., 1998).

RADAR measurements are some of the very few sources of aerial observations and effort is made to ensure that these measurements are accurate. A number of methods exist to identify and correct errors in RADAR measurements. These methods include use of rainfall gauges in the catchment to confirm results from RADAR. Another method is to use RADAR to measure rainfall in conjunction with continuous measurements of surface changes such as water flow regimes due to the rainfall events. Improvements of RADAR processing techniques, such as methods to filter the "ground clutter" effect from topographical features, is a solution for dealing with the problems that result in overestimation of rainfall (Jewitt *et al*., 1998).

Pegram and Seed (1998) pointed out that RADAR technology does not only estimate rainfall amounts at any specific location to a higher degree of accuracy with finer time and spatial resolution than rain gauges, but it also gives an accurate estimate of the spatial distribution of rainfall over large areas. The use of RADAR data is set to replace the method used to translate gauge data to area data in most models. In this method rainfall data are obtained from a number of gauges in an area then weighting factors are applied to the different gauges to get a weighted average of the rainfall. This method is used in South Africa in the following models: WRSM90, WRYM, WRPM, SHELL, Pitman and HYDRO25.

Some models use data from one rainfall station which is applied to the entire catchment. This method has been criticised for being inadequate when such models are applied to large catchments (Alexander, 1991; Mathews and Langhout, 2001). It is important to note that in all these models there are no special changes required to accommodate the RADAR data but the drawback has always been the absence of such data for reasonably long periods of at least thirty years. Typical examples of the inadequacies of rainfall inputs include those highlighted in the project to test the ACRU model on a large catchment, the Olifants catchment (Mathews and Langhout, 2001). Rainfall gauges are sparsely spaced in the Olifants catchment such that several areas larger than 50 km^2 do not have reliable rainfall gauges. The recommended rainfall network distribution in ACRU is that a maximum of 25 km^2 should have at least one representative rainfall gauge (Seed, Schulze, Dent, Lynch, and Schafer, 1995). This data requirement cannot be achieved with the available rainfall gauges such that attempts are being made to use RADAR rainfall data to supplement the point rain gauge data.

3.3.2 Runoff

Rainfall-Runoff simulations are included as important module blocks in water resources models. In the absence of runoff measurements some models can hardly be used to obtain any meaningful information because they are calibrated against recorded runoff at specific points and times. This applies to a number of locally developed models such as WRSM2000, SHELL and ACRU. The central idea in these models is that the model has to be calibrated on the basis of observed data, and if there are no observed data then there cannot be any calibration. Runoff data are usually measured using flow gauging weirs, whilst other flow measurement devices are used in isolated cases. Hughes (1997) pointed out that the use of gauging weirs has several shortcomings for the modelling processes, and important additional data should be included as part of a runoff gauge record. These data needs should include the following (Hughes, 1997):

(1) The type of gauging structure that was used,
(2) The accuracy of the records,
(3) Flags on errors and incomplete records,
(4) When was the gauging structure last calibrated?
(5) Information on rating curves used and their accuracy and

(6) The size of the structure or rating curve ranges. Are the low flows and floods measured with the same accuracy as the other flows? What is the maximum and minimum flow rate that can be measured with accuracy?

In his experiences with hydrological data outside South Africa, Hughes (1997) observed that rainfall data and runoff data are best recorded and stored by a single agent or institution. In many cases in the "FRIEND" study that involved several southern African countries, either rainfall data were obtained without the associated runoff data, or the converse. In such cases, the challenges faced in modelling and calibration meant that some important catchment simulations could not be done. Another problem resulting from the collection and storage of data by different institutions is that projects go through time-consuming and costly processes to compile the required data and, in many cases, these data sources are not complementary.

3.3.3 Evaporation

By definition, evaporation is the conversion of liquid water to water vapour at an evaporating surface and the vertical transport of vapour through the atmospheric boundary. In southern Africa an average of 91 % of the mean annual precipitation (MAP) is lost in this way making evaporation data very important inputs in water resources modelling (Kunz and Schulze, 1995). There are many methods by which evaporation data can be estimated or measured, varying from A-pan and Symon's pans, to estimations based on meteorological data (Penman, Penman-Monteith equations, *etc.*). Evaporation data when stored or sent to other people must always have details of the method that was used to collect or calculate them as these have been noted to differ due to different schools of thought and in many cases due to calculation errors. A number of South African water resources models use both the S-pan (Symon's tank evaporimeter) and the A-pan (US Weather Bureau Class A evaporimeter) data in the same model, where the S-pan data are used more commonly for open water evaporation routines and A-pan data, are used in the evapotranspiration routines where water is lost through transpiration by plants and evaporation from the soil surface. Actual determination of evapotranspiration is not easy. A specialised measuring instrument, a lysimeter, enables determination of exact water and heat balances to derive values for evaporation and evapotranspiration from a typical block of soil and vegetation.

In studies on evaporation, Raudkivi (1979) pointed out that several factors must be noted when catering for the influences of different types and degrees of plant cover on water resources modelling. Raudkivi (1979) further explained that short vegetation types, such as grass, generally transpire at the same rate as the rate with which the intercepted water would evaporate from them under the same overhead conditions.

Studies on pine forests have indicated that, through evapotranspiration pines extract large quantities of water from soil to depths approaching 30 m (Dye and Royappen, 2001). The associated reduction in soil pore water pressure significantly contributes to slope stability, but the ground water consumption by such plants is a major concern in most catchments (Dye and Royappen, 2001). Knowledge on volumes of water taken up by pine and eucalyptus forests from groundwater sources such as aquifers is still inadequate to ensure that the implications of such water uptake are incorporated in water balances and water resources modelling. Improvements to the evaporation parameters used in models have been achieved through field-based evaporation research, where a number of methods to measure evaporation and evapotranspiration in forested catchments were used and analysed over continuous periods exceeding four years (Jarmain, Govender and Everson, 2004). Measurements and analysis of evaporation was used in the ACRU agro-hydrological model as well as the SWAT soil-water balance model (Arnold, Williams, Srinivasen and King, 1999).

Studies on water use by river bank vegetation such as reeds and trees along the Sabie River system (Birkhead, Olbrich, James and Rogers, 1999) showed a number of factors related to evaporation that affected runoff in the river channel. The main findings from these studies were:

- Reeds were significant water users, using an average of 12 millimetres (mm) per day in summer and 7 mm per day in winter (That is, water lost via transpiration by reeds per unit area of reed bed was higher than from an equivalent area of open water surface).

- Transpiration rates from riparian trees was found to be 2.8 mm per day and 1.6 mm per day for summer and winter months, respectively.
- Potential evapotranspiration was always possible due to the availability of water in the river banks at saturation levels.
- It was noted that older trees and reeds had reduced transpiration rates per unit leaf area as a consequence of an obstructed hydraulic architecture caused by ageing.

3.3.4 Interception

Interception loss refers to the proportion of water caught by vegetation before reaching the ground, which is then lost through evaporation. Interception losses depend on the density and type of plants and can be as high as 25 % of annual precipitation in humid forested regions such as those found in KwaZulu-Natal province of South Africa. Interception loss plays a significant part in water balance studies. The measurement of interception involves placing rain-gauges on cleared areas where the gauge orifice has at least 90° of view unobstructed by trees or other vegetation to measure actual precipitation. Other gauges are put under tall stands of vegetation to measure throughfall. Measurement of throughfall gives highly variable results such that the number of throughfall gauges should be at least ten times those measuring total rainfall in order to improve accuracy of estimates (Raudkivi, 1979).

3.3.5 Infiltration

Precipitation that does not evaporate either becomes runoff or infiltrates into the ground, or both. Infiltration is very difficult to measure, and several studies have shown great differences in infiltration capacities of soils of different textures and structure, and of the same soil under various types of vegetation and antecedent characteristics/conditions (Lorentz, Hemme, Buitendag and Schulze, 1995; Jayawardena and Mahanama, 2002). In addition, most soils have properties that vary widely in both the vertical and horizontal directions. The soil profile affects infiltration through processes that are complicated by the growth of vegetation, biotic activity, wetting and drying and freezing and thawing. Consequently, the permeability of the soil's surface layers is seldom constant throughout an annual cycle.

Measurement of infiltration rates is complicated by the dependence of infiltration on a multitude of interacting processes. One basic method applied in South Africa is the use of infiltrometery which relies on artificial water supply to the sample area. Infiltrometers are grouped into sprinklers and flood type. The sprinkler type is designed to simulate infiltration of rainfall. The flood type simulates flood irrigation situations (Raudkivi, 1979). Data from these measurement techniques are not widely available and most models use mathematical calculations of infiltration based on user defined parameters or “mass balances” derived from gauged catchments.

3.3.6 Groundwater

Traditionally water resources management treated surface water and groundwater as if they were separate entities (WRC, 2003a). As development of land and water resources increase over time, it is apparent that development of either of these resources affects both the quantity and quality of the other. Most surface water features are linked to groundwater as water is usually exchanged between the two water resources through processes such as flow recharge and seepages. The NWA intends to build a holistic water management practice which is built on a foundation that recognizes that surface water and ground water are simply two manifestations of a single integrated resource (Republic of South Africa, 1998).

In over 80 percent of the area of South Africa, groundwater occurs in secondary aquifers (DWAF, 1986). These are generally low-yielding fractured rocks that lie directly beneath the surface to depths of less than 50 metres. Most boreholes drilled into secondary aquifers have very low yields such that water exploitation is limited to small-scale use on farms and for low volume domestic requirements. Appreciable quantities of groundwater can be abstracted from boreholes judiciously sited on dolomite. Leaching in dolomitic rocks in places to depths of 150 m, especially in the Northern Cape regions provide ideal sites for high-yield boreholes. Other locations with high volumes of groundwater are porous deposits of granular material commonly refereed to as primary aquifers. The size and distribution of primary aquifers is limited in South Africa as shown in Figure 3.2, below. In South Africa, primary aquifer formations are capable of yielding volumes of water varying between 5 and 30 percent of the gross volume of the formation. Abstraction of groundwater affects many variables in water resources models, which include stream flow recharge, water available to vegetation, evaporation, infiltration and evapotranspiration.

Little knowledge on quantitative and qualitative groundwater variables is available, such that model simulation outputs on groundwater have a larger degree of uncertainty when compared to surface water. Section 139 of the NWA (Republic of South Africa, 1998) provides for the Minister to establish national information systems regarding water resources which will include a groundwater information system. The development of the national information systems is expected to improve groundwater resources knowledge. There are current initiatives such as the National Groundwater Archive (NGA), in DWAF which incorporates detailed groundwater mapping and quantification, a meta database, analytical functionalities such as groundwater flow modelling, water balance modules, and GIS with improved graphic interfaces. Groundwater resource quantifications such as these have to be incorporated in water resources models to improve the representation of groundwater in models.

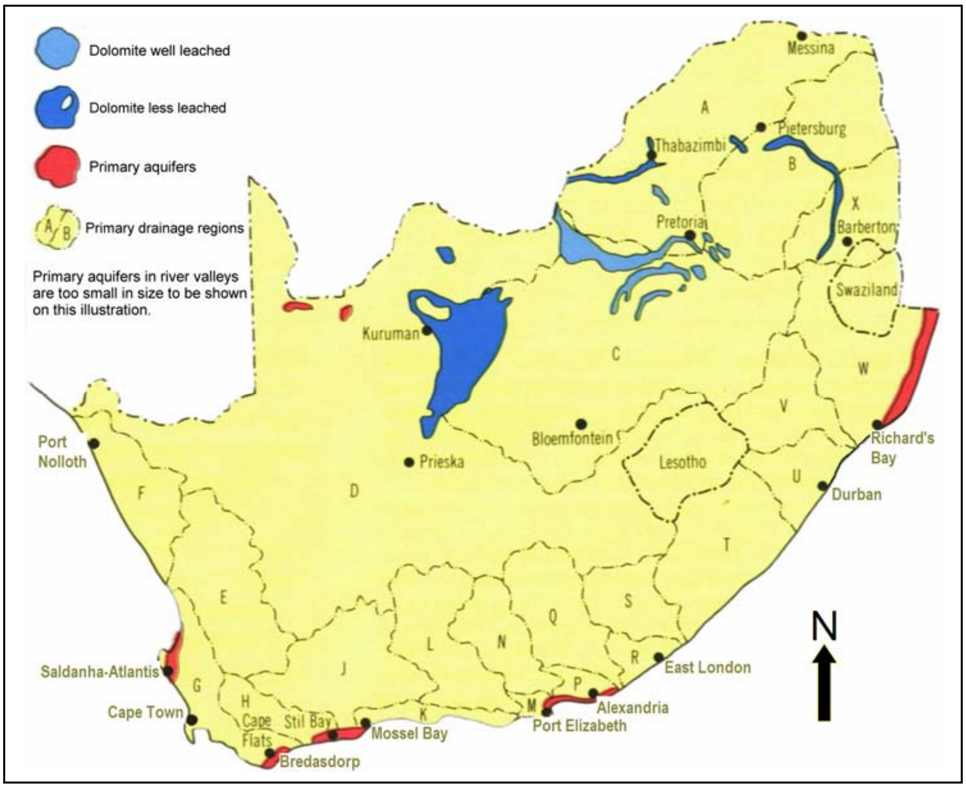


Figure 3.2 Distribution of dolomitic and primary aquifers in South Africa (Adapted from DWAF, 1986).

Groundwater usage is estimated at 14.6 % of the approximately 13 000 million cubic metres of water used per year in South Africa (Vegter, 2001). Most aquifers are not exploited to their full potential such that there is scope for increased groundwater use in most aquifers. Boreholes supplying farming areas are usually not registered with the national Department of Water Affairs and Forestry or any other institution such that irrigation use of groundwater is difficult to determine (Vegter, 2001). Most of the boreholes have no abstraction records and use is not continuous, with many cases where borehole use is only applied irregularly to supplement surface water or to provide for peak water demand periods.

3.3.7 Soils

The spatial and vertical properties of soils are important to hydrologists, for it is the capacity of the soil to absorb, retain and redistribute water that is the primary regulator of hydrological responses within a catchment in regard to the generation of stormflow, baseflow and peak discharge. The soil is the medium in and through which many other hydrological processes operate. The soil water budgeting routines that simulate the balance of water absorbed, retained and released by the soil are usually the main building blocks in rainfall-runoff models. Angus, Schulze and Guy. (1995) also noted that the most important limiting properties of the soil that affects moisture variation in a soil profile are:

- The infiltration rate at which water enters the soil at the surface, which is controlled by surface conditions; and rainfall intensity,
- The permeability rate at which water moves in the soil, which is controlled by properties of the soil horizons such as slope, and
- The water storage capacity which is dependent primarily on the soil texture and its depth.

Water resources model developers have a tendency to develop methods of representing soil-water processes that are unique for each model. This has been the case with many models including the Soil Conservation Services (SCS) model which gives a scale of 1 to 100 for the classification of soils based on soil properties and their hydrological responses. Local water resources modellers can take advantage of the technique used in the SCS model by utilising the soils classifications done by Schmidt and Schulze (1987) who classified South African soils according to hydrological responses to produce a South African version of the SCS model. Other models such as CropSyst, a water use simulation model use the percentage content of sand, clay and silt to define soil inputs.

Information on soils is usually expressed in hydrological computations by "lumping" the characteristics of many different soils found within a catchment to derive an average parameter, thus reducing model complexity and avoiding model dependence on several soil characteristics that are difficult to measure. This method which is generally easy to apply but low in accuracy is applied in models such as WRSM90, WRYM, WSAM and all the models using the Pitman rainfall-runoff routines. The ACRU model is however one of the unique models in South Africa where the spatial variation in soil types and their characteristics are included in the model to define unique sub-catchments with the aim of avoiding the lumping of soil characteristics (Angus *et al.*, 1995). On the other hand the Pitman based models (Pitman and Kakebeeke, 1993) have parameters that deal with the effects of the different soil characteristics. These include:

- Maximum soil moisture capacity;
- Runoff at soil saturation;
- Soil moisture content below which no runoff occurs;
- Runoff-soil moisture curve;
- Time lag between runoff from the soil moisture and surface flow, and
- Soil water retention capacity.

The Global Soils and Terrain Database (World-SOTER) seeks to incorporate soils from all corners of the world to be characterised under a single set of rules (FAO, 1995). In the World-SOTTER initiative, a key to the soil reference grouping which can be utilised in water resources modelling is recommend. This key reference is based on the *'soil characteristics', 'soil properties' and 'soil horizons'*. These are explained as follows:

- *Soil characteristics* are single-value soil attributes that can be observed/measured in the field or laboratory. Soil characteristics include class attributes such as colour, texture or structure class, and discrete attributes expressed in one numerical value such as ‘soil depth in cm’, ‘soil-pH’ or ‘nominal cation exchange capacity in cmol(+)/kg’.

- *Soil properties* are complex soil attributes that involve several soil characteristics and reflect present or past soil forming mechanisms. For example, ‘dark blue colour if in contact with potassium ferric cyanide’ or ‘strong red colour if sprayed with α,α-dipyridyl solution in 10 % acetic acid’ and to dynamic oxidation-reduction processes of a periodic nature.

- *Soil horizons* are internally uniform soil layers delimited by gradual, clear or abrupt upper and lower limits (‘boundaries’), and characterized by one or more soil characteristics and/or properties occurring over a specific depth.

In South Africa, field and laboratory studies on the relationship between the water regimes of soil profiles and their morphology are being used to improve model input definitions and the modelling of landscape hydrology (Van Huyssteen and du Preez, 2004). These studies rely on initiatives such as the World-SOTTER for guidance on soils characterisation.

3.3.8 Land uses and vegetation

Water processes in soils and vegetation such as interception, infiltration, evaporation, runoff regimes, evapotranspiration, throughflow, groundwater recharge and water distribution are all influenced by land uses and how these uses are managed. Human activities such as cultivation, forest clearing and paving, modify surface soil physical and hydraulic properties as well as water processes influenced by vegetation.

South African’s landuse classification is usually segmented into: cultivated areas; grazing areas; forests; conservation; settlements and "others” to cover uses such as other human developments including servitudes for roads and power lines. Roughly 12-13 %

of South Africa's land area is cultivated (DEAT, 2004). Grazing areas occupy between 19 % and 96 % of the provinces, with the lowest in Gauteng and the highest in the Northern Cape. Natural and plantation forests have been reported to be increasing due to increased commercial forests and acquisition of formal conservation areas (Hoffman, Todd, Ntshona and Turner, 1999). Hoffman *et al*. (1999) indicated that the most extensive areas of forests were distributed as follows: 4 % of the Eastern Cape, 5 % of the Western Cape and 8 % each of KwaZulu-Natal and Mpumalanga. Urbanisation is by far the greatest in Gauteng with 50 % of the total area covered by settlements (DEAT, 2004). The Eastern Cape, North West Province, KwaZulu-Natal, Western Cape and Northern Province have between 10 % and 14 % covered by settlements while other provinces have less. In the period 1995 to 2000 the annual population growth rate of South Africa was 1.57 % while urban population increased more rapidly at 1.9 % annually, such that by the year 2000, 51 % of South Africa’s population lived in urban areas (STATSSA, 2003). Rapid urban population increases without adequate settlement provisions have resulted in the establishment of thousands of informal settlements that are often called squatter camps or informal settlements in South Africa. These settlements have unique impacts on catchment hydrology. The informal settlements often have no proper sanitation facilities resulting in water quality deterioration in and around their locations. The informal settlements usually occupy any form of land that seems to be unused such as river banks, wetland areas and servitudes for roads, power lines and water pipelines. Due to their location and nature, informal settlements tend to increase flow regimes, flooding, erosion and cause other socio-hydrological problems.

The natural vegetation mapping and research in South Africa’s water resources management is based on the original research and work conducted by botanist, J. P. H. Acocks (Acocks, 1988). The Acocks vegetation database has been used as the basis for simulating land cover in South Africa (Lumsden, Jewitt and Schulze, 2003) and has been updated and improved to include changes in land use.

Initiatives to replace the Acocks classification include the work reported by Bredenkamp, Granger and van Rooyen (1996) on new national descriptions and classifications of vegetation. In this project the South African Association of Botanists and the National Botanical Institute, funded by the National Department of Environmental Affairs and Tourism (DEAT), produced a new description and classification system. In this approach, different vegetation types were delimited by teams of botanists in the following way: Each vegetation type had to be a coherent array of communities which shared common species (or abundances of species), possessed a similar vegetation structure (vertical profile), and shared the same set of ecological processes. Many water resources researchers are still using the Acocks method in projects which require vegetation classifications. In addition to the Acocks vegetation classifications, water resources modellers have applied the National Land Cover database developed by Thompson *et al*. (2000) which has allowed certain model outputs to be improved as it used recent land use data.

The Bowen Ratio Energy Balance Systems and the scintillation technique which uses the Large Aperture Scintiliometer (LAS) are some of the field-based techniques being used in South Africa to improve the accuracy of vegetation water use coefficients in models. The Large Aperture Scintiliometer (LAS) is an instrument designed for measuring the path-averaged structure parameter of the refractive index of air (Cn2) over horizontal path lengths from 250 m to 3 km. Structure parameter measurement obtained with the LAS and standard meteorological observations (air temperature, wind speed and air pressure) can be used to derive the surface sensible heat flux (Kipp Solutions, 2004).

Types of natural vegetation, agricultural practices and other anthropogenic influences (implying the influence of man-made structures such as roads, settlements and tillage of land) play a significant role in plant and soil water evaporation and evapotranspiration processes. Lecler, Hohls and Schulze (1995) pointed out three primary groupings of factors where land use and vegetation affected hydrological modelling. The three groups are:

(1) Above ground factors, implying canopy interception losses, consumptive water use by plants, shading of the soil thereby separating total evaporation into evaporation of the water from the soil and uptake of water into plant tissue
(2) Surface factors, which focus on protection by the plant/litter cover against erosion
(3) Below ground factors, concerned with plant root distribution, root water uptake and the onset of plant water stress.

The modelling of water resources using time series data requires additional inputs to account for the historical changes in land use factors with time (Görgens and Howard, 1994). Land use changes with time mean that all the factors mentioned in groups (1) to (3) above are also changing. These changes have to be included in water resources assessments to ensure up to date simulations.

3.3.9 Weather and climate

Several climatic characteristics interact to produce a wide array of different climates, such that no two places experience identical climates (Ahrens, 1994). However, the similarity of climates in a given area allows one to divide the earth into broad climatic regions. The divisions of the earth into climatic types have been developed based on rainfall, temperature, wind, latitude and the distribution of vegetation (Blair, 1951). Figure 3.3 below shows rainfall seasonality in South Africa which can be used to distinguish climatic zones.

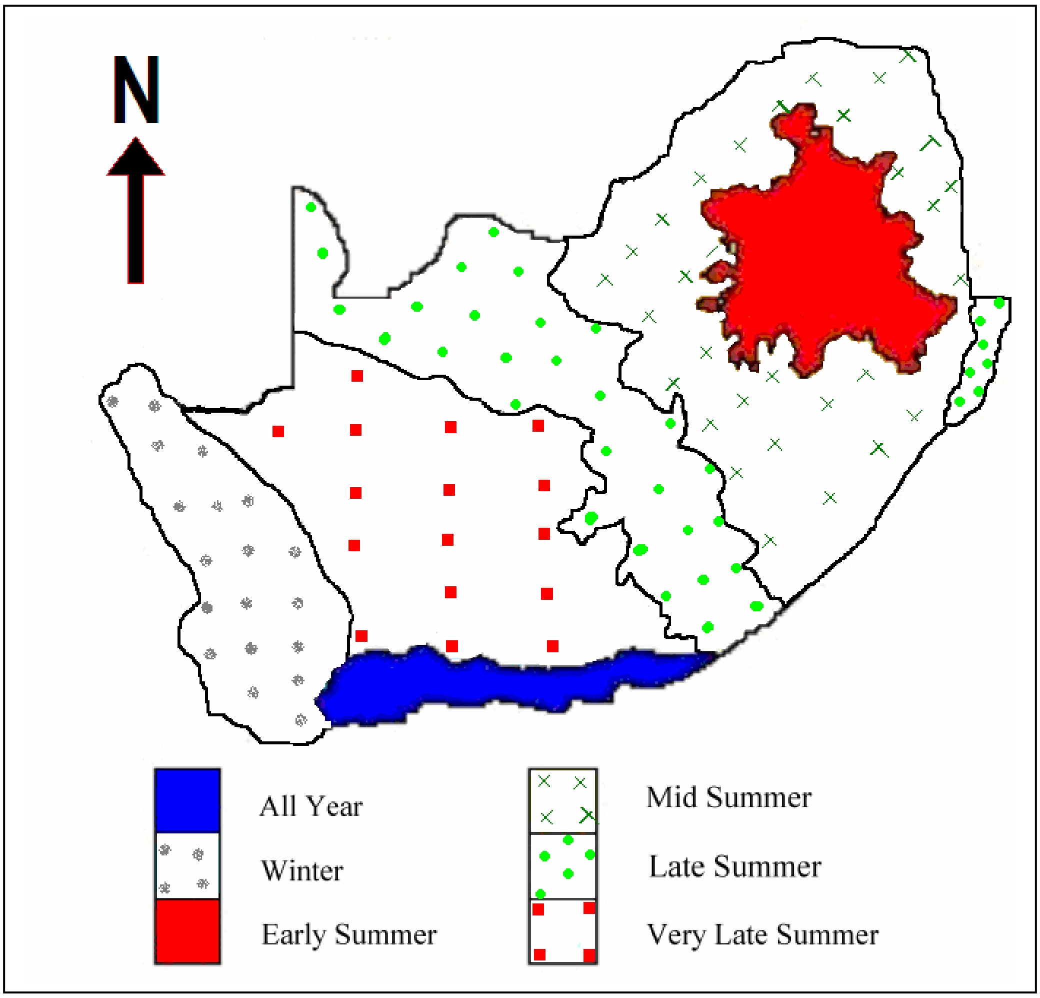


Figure 3.3 **Map showing rainfall seasonality over South Africa (Redrawn from Lynch, 2003).**

In water resources modelling, most of the factors that affect the water budget, namely precipitation, evapotranspiration, moisture storage in the soil, surface runoff and the movement of water through the root zone in the soil, are either basic climatic parameters or are related to them. Availability of weather and climate data, the length of data records and their reliability, affect the choices of the tools to be used to plan and manage water resources effectively and accurately.

Rainfall is a core input in water resources modelling. While rainfall is measured at approximately 2 800 active point locations (Lynch, 2003), the variables: air temperature, evaporation, surface wind speed and direction, atmospheric humidity, atmospheric pressure and duration (hours) of bright sunshine are usually measured at far fewer weather stations, where measurements are mostly non-continuous and made for specific reasons. However, most water resources models currently used in South Africa depend mainly on recorded rainfall data or have options to use simulated data that has been derived from stochastic models.

The South African Weather Service (SAWS) with 1855 (SAWS, 2001) weather stations operates the majority of the active weather stations in South Africa. These stations are grouped into 48 First order stations, 27 Second order stations, 80 Third order stations and 1700 rainfall gauges. Each station category has a particular set of instruments issued to it as shown in Table 3.1 below.

The tendency in South Africa is to use models that do not require high resolution data inputs of say continuous daily or shorter intervals, or area components at plot scale for large-scale planning and management such as quaternary scale, because detailed data are only available for very limited areas. Ideally, a more dense distribution of weather recording stations giving more details in time and space is an important aspect of high resolution water resources modelling. This provides increased accuracy in the information generated by the models and ensures that plans made on the basis of this information are more efficient and applicable.

Table 3.1 Weather station instruments in each SAWS class of weather station (Adapted from Gill, 2004).

Weather Instrument	Station order		
	1st	2nd	3rd
Stevenson screen	Y	Y	Y
Max- and min thermometers	Y	Y	Y
Dry- and wet bulb thermometers	Y	Y	(Y)
Thermohygrograph	Y	Y	(Y)
Thermograph			(Y)
Standard 127 mm raingauge	Y	Y	Y
Pressure plate anemometer	Y	(Y)	(Y)
Anemometer	Y	Y	
Sunshine recorder	Y	(Y)	
Barometer	Y		
Barograph	Y		
(Y) Indicates optional			

3.3.10 River systems

South Africa's water demand is concentrated in relatively few locations such that water demand in these specific areas exceeds the water available in nearby catchments. A system of water transfers from distant catchments is utilised to provide for the excess demand in those areas where demand exceeds supply. The Gauteng province is one area where water demand far exceeds the water available in the region and water provision to this province and surrounding areas is currently achieved by means of an intricate system of water transfers to the Vaal River system, as illustrated in Figure 3.4 below. Water transfer schemes have major impacts on the aquatic ecosystems of the rivers where water is being abstracted, and also the receiving rivers where "additional" water flows. Kornis and Laczay (1988) pointed out that rivers or river-reaches in an undisturbed regime maintain or at least try to maintain the slope-conditions, channel pattern and hydraulic geometry in or around the state of dynamic equilibrium. The scale of water transfers required in the case of South African cities have meant that significant considerations should be made to determine ecosystem impacts. Of importance in these considerations are the environmental requirements provided for in the NWA. Very costly and detailed investigations are required in projects such as the major water transfer schemes. As an example DWAF invested R29 million in the Thukela Water Project (TWP) feasibility studies. This water transfer scheme is very important for the country's water provision but is likely to have major impacts to donor and recipient ecosystems. The TWP is expected to transfer an additional 15 m^3/s of water to the Vaal River System (VRS) (DWAF, 2001a). At least two major dams (Jana and Mielietuin) and a system of water tunnels, pipelines and pump facilities to overcome a head of up to 200 m over the Drakensberg escarpment into the VRS are planned in this project.

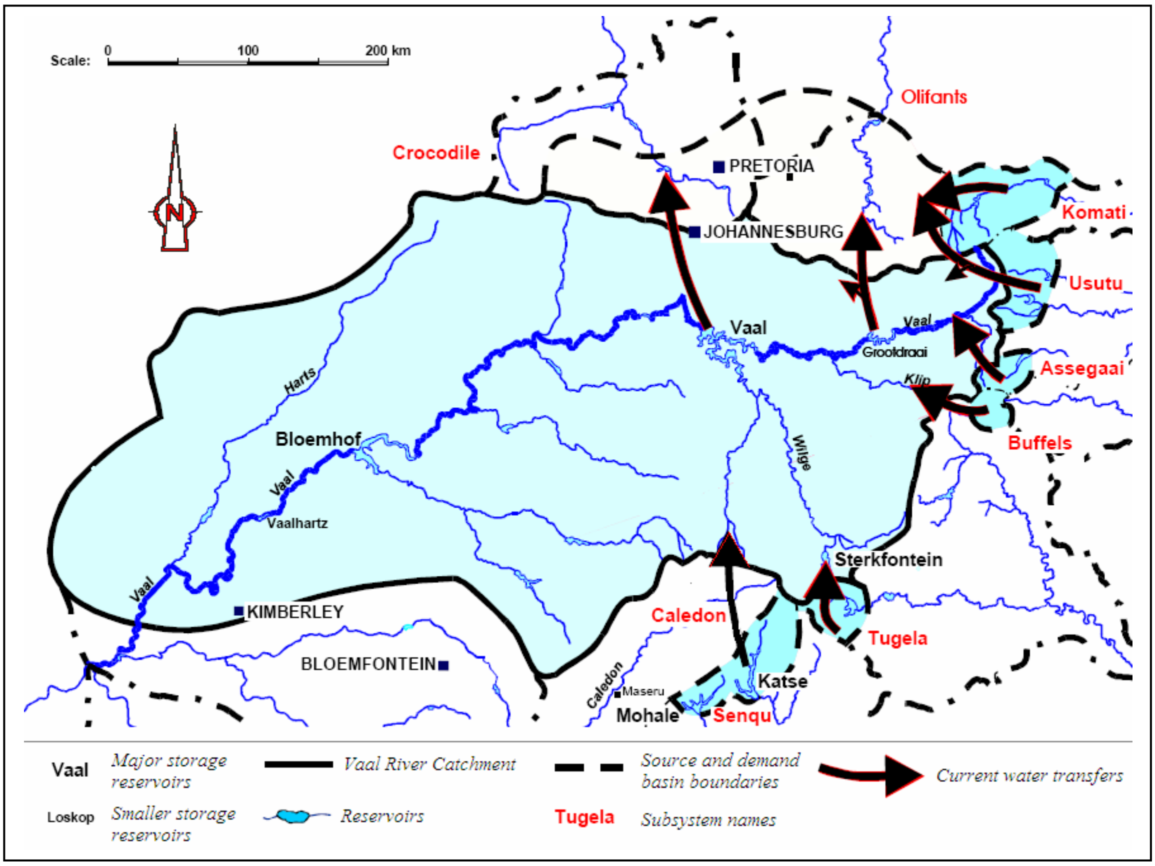


Figure 3.4 **Vaal River system water supply area and water transfers (Adapted from DWAF, 1998a).**

South Africa has a number of large man-made water resources infrastructure components, especially dams and water tunnels which contribute to water management and planning complexities, especially in water resources modelling processes. Some important examples of this infrastructure from the Orange River include the following (DWAF, 1997b):

- Phase 1 (a) and (b) of LHWP, which supplements the water resources of the Vaal River system by 30 m^3/s,
- The 83 km Orange-Fish tunnel transferring 54 m^3/s from Gariep Dam on the Orange River to the Sundays River in the Eastern Cape region,
- The 103 km long Klipfontein-Darlington canal with a capacity of 9.9 m^3/s mostly utilised by irrigators,
- The twice a day, short-duration peak releases of 720 m^3/s for hydro-electric power turbines supplied by Gariep and Vanderkloof Dam,
- The Orange-Riet transfer scheme which transfers 57 m^3/s of water from the Vanderkloof Dam on the Orange River to the Vanderkloof Right and Left bank canals, which feed water by gravity and pumping in some sections to supply settlements and farming areas in the Orange Free State and the Karoo,
- Compensation releases from Gariep Dam, where a constant release of 16 m^3/s is made for the purpose of irrigating 1 713 ha of land along the lower Orange River.

South African rivers are in the process of being classified according to resource quality objectives, followed by a process to determine and provide for the reserve (Section 16 of the NWA, Republic of South Africa, 1998). According to the NWA the reserve consists of two parts: the basic human needs reserve and the ecological reserve. The water availability or yield in river systems will be altered in accordance with the recommendations coming out of the water resources classifications. In cases where the water reserve is not being met, the requirement of the NWA is expected to be followed. This requirement states that the water available for other uses will be reduced to meet the reserve in cases of water shortages.

A number of South African rivers are fed by sediment-polluted streams passing through poorly managed catchments where extensive erosion takes place. Like other forms of pollution, sedimentation reduces water availability and alters river channel hydraulics due to the cohesive action of the flow regime and the deposition of sediments. One example of very high levels of sediment pollution is the Caledon River supplying the Welbedacht Dam which carries over 15 million tonnes of sediments per year. DWAF (1997a) reported that the Welbedacht dam reservoir capacity was reduced from 114 million m^3 in 1973 to 20 million m^3 in 1994 through sedimentation. An additional storage, Knellpoort Dam had to be developed urgently to supplement water storage for the city of Bloemfontein. Planning and management in water resources has to account for sedimentation if water availability and reliability of supply is to be considered.

3.4 Technology and the human factors in water resources modelling

3.4.1 Water resources modelling software and technology in South Africa

South Africa, like any other country suffers from a general tendency to resist new technology in the IT sector (Stam, Stanton and Guzman, 2003). Water resources model users are not excluded from this trend, they also have a general tendency to resist new technology, and more so if they have had other discouraging experiences in the past. This problem is exaggerated in South Africa because of the existence of an older science community mostly above 50 years of age (DST, 2002) who are involved in the use and development of new modelling tools. Older scientists have been observed to resist new technology more than the younger generation. Stam, Stanton and Guzman (2003) also noted that attitudes towards using new technology are a function of two belief constructs: perceived usefulness of the technology and perceived ease of use of the technology. A visible trend can be noticed in the South African water resources industry, where stakeholders have little faith in the usefulness of new IT tools such as new models but rather focus on working with and upgrading existing tools (SRK, 2004). The requirements for water management in the NWA point to the need for new tools which have smaller spatial scales and higher temporal resolutions to support shorter-term CMA planning and operations. Practitioners, researchers and other stakeholders in the water sector appreciate the need for a thorough review of all technology used in water management and planning in line with the NWA, but tend to go back to existing tools and attempt to redevelop these to meet the new requirements rather than working on well targeted new solutions. The tendency to avoid new higher resolution modelling that will be more applicable at CMA level is best illustrated by the stakeholder support for new research initiatives in hydrology that tend to focus on using monthly models instead of daily and other higher resolution time steps (WRC, 2003a). The tendency to concentrate on existing tools in water resources model developments is evident in a number of model development initiatives. These initiatives include: the ACRU model upgrading works at the University of KwaZulu-Natal, additions of different types of routines to the Pitman model including the development of user support routines in the model, WRSM2000 (SSC, 2001), and the additions of a GIS package to the Pitman Model in the SPATSIM software (Hughes, 2003). The upgrading of the WRYM and WRPM (Watson, Haasbroek, and Nyabeze, 2003) have also focussed on reformatting existing monthly models to add user friendly routines. Ideally, developments in water resources modelling should take place in the both new and existing software to address the needs for new model formulation and avoid situations where existing tools become outdated and mostly inapplicable.

South African model developers and key role players have not been very creative in defining guidance for the type of software and processes to be followed by developers of water resources management software tools. Hughes *et al*. (2004) have suggested some of the reasons why the level of modelling tool development in South Africa is where it is. Reasons given include the small South African modelling market and user preferences in modelling. As a result, cases of a single model being developed and upgraded by non-coordinated teams using a number of programming languages are common. The ACRU model is one example where at least three different programming languages were used in one model. While it is important to utilise the language that gives the best advantages such as Fortran for fast mathematical calculations, Java for good interfacing and Visual Basic for user friendly graphical Windows, there is a need to seek uniformity in the modelling process within one model and allow for easier understanding and upgrading of tools in the future. DWAF, a major client in water resources modelling projects, has developed some user specifications that require code developments to be done in Delphi code for national water management projects. Specific guidance such as what DWAF seeks to establish in water resources is important, but the enforcement of a single language in programming requires proper appreciation of the possible implications. Observations from a study to evaluate sustainability of water resources models indicated that restricting developers to one language can have negative impact on their creativity (Hughes *et al.,* 2004). This author has also observed that model developers will do well when guidance is given in terms of the expectations on product functionality and the final deliverable rather than defining strictly the way to get this final output. Recent developments in the Water Research Commission (WRC)'s projects have clearly shown that models developed using most of the available languages used locally in the water resources sector can be interfaced such that they can be promoted to gain the advantages of Object Oriented Programming (OOP). Oxley *et al*. (2002) provided a detailed case study in which wrapping techniques were used to integrate models developed in different languages into a single DSS. The models were first converted from their native language into ActiveX model building blocks (MBB) using minor recoding. The wrapping process was tailored to each MBB. Standard interface definitions, the hallmark of ActiveX, were used to integrate each MBB with the windows operating system. The integration of models such as the use of MBB developed in different languages is very important to water resources managers as it facilitates a holistic simulation process that incorporates all possible water resources processes.

Schilling (2002) observed that model development today can be done in real time and online, allowing stakeholders to participate and shape the final solution. He pointed out that this was a major change from previous trends where experts listened, then went away and built brilliant models that only they could manipulate, and which ended up being seen as "black boxes" in the eyes of users and decision-makers. This new trend is likely to gain support in South Africa as the developers of key models are being encouraged to put their source code for free local access, a recent example is the WRYM source code which is now available through DWAF.

GIS use in water resources models is applied in South Africa in a limited number of models at a very low level. South African models such as ACRU, WRYM and SPATISM utilise GIS for basic spatial representation (*loose coupling*) and have not yet developed integrated GIS coupling which McKinney *et al*. (1999) referred to as *tight coupling*. Tight coupling is defined as the case where the model, GIS and all their data are imbedded in a single manipulation framework. Tight coupling requires the use of Object Oriented programming where the water or environmental system is perceived as consisting of thematic objects integrated with GIS's spatial objects. Water systems with tight coupling include the ArcGis Hydro (Maidment, 2001) and Water Ware (Fedra and Jamieson, 1996).

Multi-scale approaches are very important in environmental and land use models such as water resources management and planning models. The need to simulate environmental processes at daily time steps, and then scale them up or switch them to monthly scales while also changing spatial scales from field scale to quaternary catchments, is an approach that generates suitable answers to decision making problems at different resolution. Polhill, Gotts and Law (2002) explained that object oriented (OO) programming alone lacks a constructive way of linking the scales in the required hierarchies. The addition of a relational modelling approach where tables are used to store data for each scale is advised (Polhill *et al.*, 2002). While this approach has not been practiced in local models, other data intensive options to vary scales using unconnected text files have been applied in models such as ACRU and WQ2000 (Herold, 2003).

3.4.2 Available manpower and their expertise

Water resources management and planning requires a great deal of expertise in science and research. The South African Department of Science and Technology reported that the number of science experts in the country are rapidly dwindling (DST, 2002). The need to develop younger scientists to replace an aging population with a current average age of over 50 years has been noted. Figure 3.5 below shows the distribution of key science researchers in South Africa on the basis of technical science publications in the 1990s. A general trend of an aging population of researchers can be observed. This trend is due to several factors which include:

- Migration of professionals to countries that are perceived as offering higher salaries and better livelihood opportunities.
- Reduced availability of funding in the sciences field per researcher as new players come into the water sector.
- A tendency for “job hopping” that is becoming an unfortunate part of the South African employment patterns has also reduced the time available for employees to contribute meaningfully. Employers are losing many months of useful productivity on each employee who is changes jobs.

- Reduced life expectancies in South Africa mean that the new scientists are lost at earlier ages than in the past. The HIV/AIDS pandemic is the main cause of these early deaths.

Younger people have shown a declining interest in science and mathematics during the last twenty years. Since these subjects are critical for water resources planning and management, these disciplines have also been noted to have gone down over the years (DST, 2002). Schilling (2002) observed that the problem of dwindling numbers of younger science specialists in water resources planning is an international problem. In his surveys on planning students, he observed that younger personnel and students in planning preferred to take jobs with higher paying private sector firms where their tasks are usually well-defined, as opposed to public agencies. This trend directily affects water resources planning and management which are usually done through public agencies.

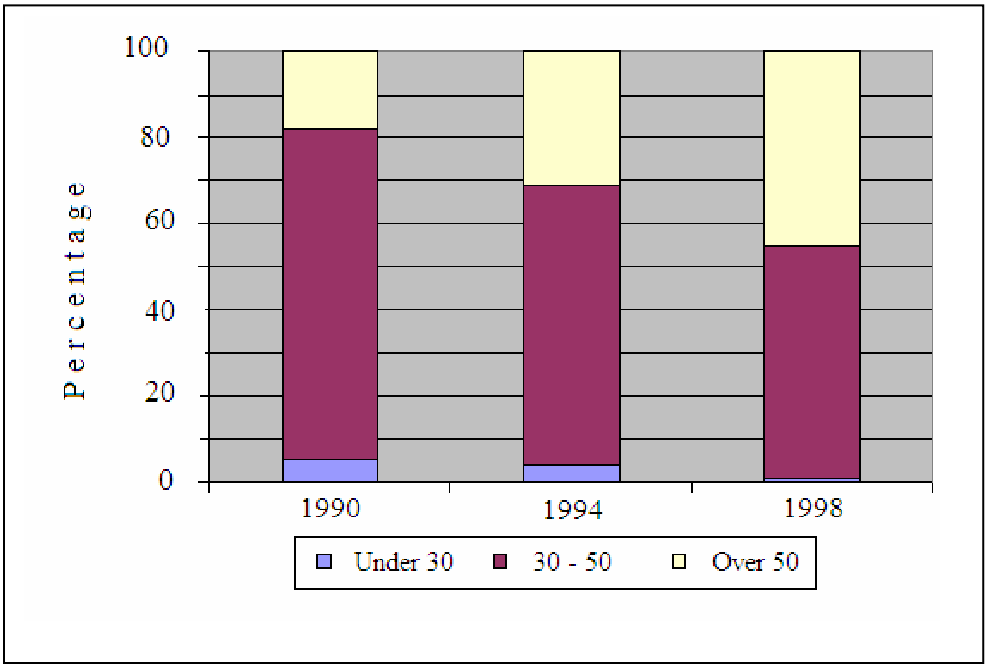


Figure 3.5 **Changes in the age patterns of scientists publishing technical articles since 1990 (Adapted from DST, 2002).**

An aging population of experts and research scientists within the water resources sector as well as emigration have meant that the trend to take new approaches is usually an unpopular route. This is one of the reasons for the persistent development of outdated approaches and, in some cases, the use of MS-DOS based programmes, despite a lack of confirmed support from the original code sources like Microsoft. As an example, Microsoft no longer includes or support some key MS-DOS files in new Windows operating systems, but some model developers are busy developing tools in MS-DOS. One such recent development is the gridded daily rainfall project software presented in Lynch (2003) which cannot run in some recent versions of Windows operating systems. Current university graduates and other new users of software are no longer getting training on some of the older software languages such as MS-DOS.

The use of suitable and qualified expertise in water resources planning and management model development is usually avoided as scientists tend to favour low cost own-developments that do not involve costly external software experts. While the trend has been that the scientists and water resources experts end up developing the models including the actual coding, a recent project (Hughes *et al*., 2004) pointed out that this approach has very limited benefits. The approach fails to take advantage of expert programmers' inputs which are essential in the development of commercially and technically viable software. Models that utilise expert programmers have managed to have a better following and significant acceptance and support by stakeholders due to many other added qualities that include user friendliness, conformity to current operating environments and well-documented user support which uses help facilities and error handling procedures. One model that used expert programmers is the WRSM2000 (SSC, 2001) model which is currently sold to users at a cost of R3400.00 including training, making it more expensive than most locally developed models. However, it continues to attract significant users making it an example of a success story in local water resources model commercialisation (Hughes *et al*., 2004).

The development of specialists in South Africa's water resources management sector is constrained by the size of the water management market. With a small local water industry in South Africa, there are few employment opportunities for specialists who are solely employed to develop water resources models as is the case in larger and more developed water sectors, especially in the developed nations. As a result, water resources model developers are usually scientists at universities or other experts who are already employed to carry out a wide range of other job functions that have little relationship to water resources model development. These practitioners are usually better suited to handle the development of concepts and equations behind the model, but end up having to spend significant amounts of their time and other resources writing the actual model code. The model solutions developed in this manner are usually underdeveloped and restricted to specific problems and fail to adequately address all the variables involved. Cases of some surface water models failing to adequately address other variables such as those associated with groundwater, water quality and soils to the same extent as how rainfall and evaporation is handled are common in local models (Hensley, 2004). Hensley (2004) also explained that physical models that use conceptual methods such as the SCS technique for determining runoff regime were extremely coarse in how they handled soil physical characteristics and coefficients. Hensley suggested the use of methods which are based on detailed physical characteristics where soils characteristics are represented as well as other hydrological inputs such as rainfall and evaporation to avoid situations where the soils variables inputs become the limiting factor in model performance.

Project implementation teams in water resources management and planning have to include all the role players. In an assessment to evaluate requirements for environmental flow projects such as water resources planning, Davis and Hirji (2003), advised the need for the following features in special expertise:

- Exprienced specialists, with first-hand knowledge of the rivers of concern, in the flow-related aspects of the following disciplines: hydrology, geohydrology, hydraulics, geomorphology, sedimentology, water chemistry, biotic integrity, physical habitat, riparian and instream vegetation, fish, invertebrates, and possibly herpetofauna and terrestrial wildlife.
- If socio-economic aspects are to be included in the assessment, specialists in the following disciplines may be required: sociology, human geography, anthropology, public health, domestic-stock health, resource and project economics, and public participation procedures. Also required are specialists with knowledge of the flow-related aspects of waterborne diseases, and those of parasites and/or their hosts.

Private and public institutions have also identified the need to address critical shortages of professionals in Water Engineering and Management. There ere a number of capacity building processes which are being implemented in South Africa. Some of the key initiatives that are aimed at addressing the shortages of professionals include:

- The development of a suitable education base in mathematics and sciences. Examples include, the African Institute for Mathematical Sciences which was established and opened in South Africa in 2003. Other national processes for addressing shortages in sciences and mathematics include ensuring that mathematics is compulsory for all South African students. The national target of eliminating fees for the poorest quintile of primary schools is another process that addresses the underlying problems of professional shortages. 529 schools will be assisted through this process, thus doubling the Maths and Science graduate output to 50 000 by 2008 (Mbeki, 2006).
- Incentives are applied to engage and retain professionals in areas that are facing skills shortages such as water resources engineering and management,
- Establishment of the Sector Education and Training Authorities (SETA) which ensures and support the development of skills in work places,
- Improved processes for hiring expatriate professionals in areas that are experiencing shortages. This is facilitated by the Immigration Act (Act No 13 of 2002) and amendments to the emigration policy (Government Gazette, 2002),
- Targeted research funding where researchers are guided into building interdisciplinary research teams. Many research and development institutions including the WRC follow this project structure (WRC, 2003a),
- University degrees that provide for interaction between disciplines, for example ecological-hydraulics studies and research projects that are offered in the Engineering Faculty at the University of Witwatersrand,
- The National Research Foundation (NRF)'s capacity building programme for the water sector which aims to build professional and institutional capacity (NRF, 2005).

3.4.3 Research and development initiatives and their funding

Water resources management and planning work usually takes place in projects where the Government is the client and needs to fulfil its role as the custodian of the public resource, water. Research institutions such as the WRC, Council for Scientific and Industrial Research (CSIR), Agricultural Research Council (ARC), International Water Management Institute (IMWI) and research departments in other organizations such as water utilities seek to fund research that is beneficial to the nation and attempt to tailor their research activities in alignment with national policies and their own mandates. South Africa, like many developing countries, has an enormous need for research and development in technical planning and management which is difficult to satisfy with the available financial resources. DST (2002) noted that the total public and private sector expenditure on research and development in South Africa is low, and has declined steadily from levels of 1.1 % of Gross Domestic Product (GDP) in 1990 to a 0.7 % in 2002. South Africa needs more investment in research; its funding levels in research and development are significantly lower when compared with other countries such as Sweden with a similar population size. Sweden currently spends more than 3.5 % of its GDP on research and development. The research needs in developing countries compete with the need to address other more urgent issues such as widespread disease, poverty and many socio-economic issues which usually receive higher priority in national funding programmes.

The funding of research and development in the water sector is a major challenge in developing countries where most of the water use is dominated by agriculture, which is usually the least efficient water use. A study in the Orange River (DWAF, 1997c) showed that agriculture utilised more than 60 % of the water in the region and accounted for an additional 20 % of water losses, while contributing less than 8 % of the GDP. Abernethy (2000) explained that the water use patterns in developed countries and developing countries are radically different. He noted that while industrial users predominate in developed countries, the industrial category is seldom well developed in poorer countries, where up to 89 % of abstracted water is used for agriculture. Because agriculture generates less revenue per unit of water used, research and development funding is also lower, when compared to research in highly industrialised nations where each unit of water has a higher value attached to it. Examples of this type of difference are shown in Table 3.2 below for South Africa.

Abernethy (2000) also noted that water use patterns have great influence on the ability of the water sector to finance water research and development. Abernethy (2000) pointed out that while industrial users usually emphasise few large-capacity consumers dealing in profitable activities, the agricultural users are usually numerous, and form the bulk of the population in developing countries whose financial resources are very meagre. This explains some of the causes of the lower funding levels for initiatives such as water resources planning and management in developing countries like South Africa.

Table 3.2 Sectoral consumption of water (Adapted from Abernethy, 2000).
(Units: % of annual freshwater abstraction.)

Income category	**Sector**		
	Agriculture	**Domestic**	**Industrial**
Low Income	89	4	7
Low middle income	77	8	8
Upper middle income	73	12	15
High income	40	15	45

Cost recovery is an important aspect of water projects including the planning and management process. A number of initiatives have been established in many countries where scientists and technologists are encouraged to commercialise their work, such that research and other aspects of planning and management are commercially viable (Gascoigne and Metcalfe, 1999; ARC, 2000). Gascoigne and Metcalfe (1999) also observed that the success of such commercialisation is dependent on the presence of large supporting industries, government support, taxation systems, attitudes and the understanding of scientists and technologists, as well as the adequacy of available financial advice. Commercialisation of some aspects of water resources planning and management, such as the research component, leverages the funding available and builds the required continuity of these processes that are usually terminated prematurely when funding is stopped or postponed. The Agriculture Research Council (ARC) also investigated the process of commercialising research (ARC, 2000) and identified the following key factors concerning the broad environment in which commercialisation takes place:

- The quality of the research base and the maintenance of science and technology skills;
- The availability of companies willing and able to take up the results of research;
- The strength of links between the research base and industry;

- Availability of venture capital;
- The quality of management skills; and
- An appropriate regulatory environment.

Studies on the commercialisation of water resources models developed in South Africa have revealed the need for continuous funding (Hughes *et al.*, 2004). The study revealed that several key water resources model developments in South Africa could not sustain themselves on the income generated through sales of models, but required external funding from other organisations especially those organisations funding research. This funding is now threatened by a research environment where research objectives have to be aligned with the revised national priorities as portrayed in national legal tools such as the NWA and the National Strategy on Research and Development. This has resulted in major challenges in goal setting, delivery, and performance in the different organisations and individuals involved in research.

3.4.4 Data availability and quality

The quality and availability of data are of critical importance in water resources modelling. The quality of information generated by a water resources management or planning model depends on the quality and representativeness of the input data (Hughes, 1997).

Collection and storage of water resources data and information in southern Africa needs accelerated development and a process of centralisation (Republic of South Africa, 1998). A number of institutions working on different water resources projects or other initiatives are involved in data collection and storage without linking to a national system (Hughes, 1997). Collating such data from different sources is a major challenge that requires a lot of resources such that water practitioners attach high costs to the collection, analysis and storage of such data. Chapter 14 of the NWA requires the establishment of national monitoring systems to facilitate the continued and coordinated monitoring of various aspects of water resources by collecting relevant data and information. Processes have already been established to develop (Republic of South Africa, 1998) the data and information systems for various aspects of water resources through national projects such as DWAF's National Information Systems (NIS), the National Spatial Information Framework (NSIF), the National Groundwater Database (NGDB) and the National Water Quality Database (QUALDB).

The implementation of successful water resources management and planning requires a number of data and tool features, which include:

- Continuous and accurate long-term hydrological data for the whole country,
- Hydrological models with detailed time steps of daily and smaller resolution scales,
- Linked surface, groundwater and water quality models,
- Long-term water chemistry records for all variables required for water resources planning and management. Davis and Hirji (2003) suggested that it is important to link the water chemistry records to hydrographs,
- Appropriate flow assessment methodologies,
- Comprehensive data on the distribution, life histories, and flow-related habitat requirements of riverine species. Similar data for the abiotic aspects of rivers where relevant, for estuaries and coastal marine environments (Davis and Hirji, 2003),
- A well-structured link between river and estuary flow assessments, where appropriate,
- Responses of the hydrological system to man-induced changes (Schulze,1998),
- Appropriate water resources risk assessment methodologies (Schulze,1998),
- Knowledge of climate change and its implications for long term planning,
- Details of the dynamics of human populations and settlement distributions.

One other significant feature of South African hydrological data is that most data resources are concentrated in the higher rainfall areas that have benefited from numerous hydrological studies located in these areas. Many research groups and practitioners in water resources including DWAF, CSIR, Working for Water Programme (WfW), School of Bioresources Engineering and Environmental Hydrology (SBEEH), the Soils Research Group at the University of the Orange Free State, and private consulting groups, tend to utilise wet catchments with readily available data for field measurements and research. The drier catchments are "data poor" and present difficulties in setting up new databases which takes many years.

An important option in resolving the need for data is the use of data generating models. These are models that mimic the statistics of the historical records and transfer the statistics to areas where data are missing. Rainfall, the main data component of water resources models, can be generated using models that fall into three broad groups, namely: empirical statistical, dynamic meteorological, and intermediate stochastic models (Cox and Isham, 1994). Empirical statistical models are the most important for data generation. They are based on empirical analysis of rain gauge records. Empirical models include stochastic, single-site, multi-site, and downscaling rainfall generation models. Stochastic modelling is the most commonly applied technique in hydrological data generation. Rainfall generation techniques are widely applied in South Africa because of the lack of sufficient data for time series simulations. In some models, the stochastic routines have created outstanding and unique South African model routines where data scarcity is adequately addressed (Pegram and Seed, 1998). As an example, the stochastic data generators developed by Pegram (1986) have been used in the WRYM and the WRPM to simulate a range of national planning scenarios stretching over thousands of years of synthetic data thus allowing more accurate determination of water management and use risk for different national or basin level plans. The stochastic data generators used in South Africa’s systems models are unique to the country as they were developed to deal with specific climate characteristics and the unique data scarcity problems inherent in the country (BKS, 1986).

Ideally, data generation, especially stochastic hydrological data should constitute a key component of water resources planning and management in data poor countries such as South Africa. The improvement of data generation techniques to incorporate other existing data such as the isolated field gauges and records from remote sensing will add value and improve the availability of data in South Africa.

3.4.5 Geographical Information Systems and Digital Elevation Models

Geographical Information Systems (GIS) are essential in water resources management as a platform for the presentation of spatial dimensions (Walsh, 1992). Colins and Campell (2003) observed that the abilities of GIS stretched beyond its use simply as a mapping tool. The under-utilisation of GIS in modelling was blamed on the lack of awareness, limited experience, inadequate initiatives to experiment with new methods and the costs involved. Often GIS is used simply as a mapping object in water resources problems. McKinney *et al.* (1999) noted that the use of GIS could assist in problem and solution visualisation, analysis of model inputs and outputs, model supporting and problem management.

Water resources management and planning techniques can incorporate GIS through a number of methods which include specialised tools such as Spatial Decision Support Systems (SDSS) where an interactive decision support system is built on a GIS platform (McKinney *et al.*, 1999; Larsen *et al.*, 2004), or through other forms of loose GIS coupling where GIS is simply added to a water resources model as a mapping object. Larsen *et al.* (2004) described the MIKE INFO data architecture as an illustration of a combination of models and GIS, that efficiently share a common platform for pre- and post- processing of data. Figure 3.6 below presents an illustration of the MIKE INFO data architecture.

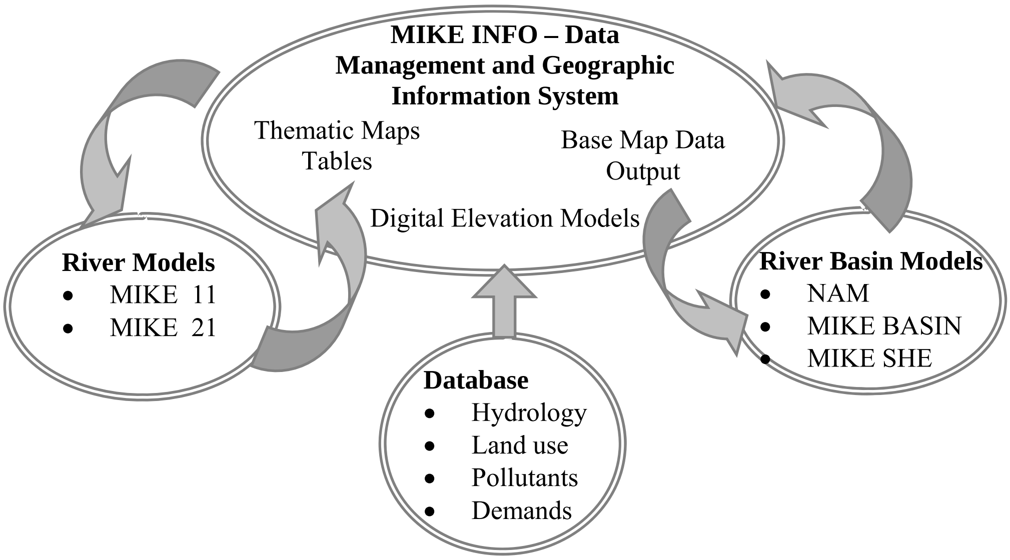


Figure 3.6 Integrated MIKE INFO system for river basin management (Redrawn from Larsen *et al.*, 2004).

GIS platforms require accurate and detailed spatial data. DTMs are very important sources of detailed spatial references and elevation data. While DTMs are more readily available than ground surveys their accuracy is usually limited to within +/-25cm (vertically and horizontally) while ground surveys provide better accuracy, often as good as +/-5 cm (Collins and Campbell, 2003). Despite the indicated inaccuracies, the use of

DTMs in South Africa will be a major step in improving local accuracy levels in most water resources studies, which currently depend on coarser spatial scales such as the use of 1: 50 000 maps as the main source of GIS data. In fact, the majority of local water resources models are run at time steps of one day or longer with spatial scales ranging from grid scales (1 km X 1 km) to quaternary scales spanning thousands of square kilometres. GIS applications are shifting towards packages which can provide the possibility of creating 3D visualisation of the model results, which can then be overlaid on to DTMs or other similar surfaces, offering an improved understanding of the problem in the real world (Colins and Campbell, 2003). South African practitioners utilize a number of packages with 3D models such as:

- MapInfo Vertical Mapper,
- ArcGIS 3D and Spatial Analyst,
- Intergraph Dynamo Terrain Modeller and
- CAICE 3D modeller.

The integration of spatial, point, numerical, temporal, and other data is an important aspect in the coupling of GIS and water resources models. McKinney *et al.* (1999) described approaches and strategies for the coupling of environmental models and GIS which range from loose to tight coupling. Loose coupling consists of the transfer of data between GIS and numerical models; it is based on two separate systems and, generally, separate data management. Transfer of data is accomplished by writing and reading ASCII text files. Tight coupling involves integrated data management, in which the GIS and the models share the same database platform. Collins and Campbell (2003) advised practitioners to use data translation software packages, such as Feature Manipulation Engines (FME) which allow data to be translated easily between conventional and more bespoke software to meet a variety of needs. The approach used in the InfoWorks from Wallingford, uses a combination of models sharing a common data platform with the GIS (Larsen *et al*., 2004).

The establishment of a common approach in GIS application in water resources and indeed other environmental management applications has been hampered by a number of factors, including:

- GIS software applications are imported at high costs, mostly from ESRI, which maintains strict licensing and copyright procedures. As an example, the ArcGIS package, which is ESRI's current complete GIS package costs more than R193 000 (GIMS, 2003).
- GIS software is continuously being upgraded along commercial values that are not aligned to the local user needs. As an example, ESRI's ArcGIS package comes with its own ArcView, ArchInfo and Spatial analyst, such that users will not benefit if they intend to keep the older software.
- Water resources practitioners have inadequate appreciation and understanding of GIS (Collins and Campbell, 2003).
- Lack of suitable technical guidance, framework and policies is provided for the use of GIS in water resources planning and management.
- Limited availability and the high costs of obtaining GIS data (Collins and Campbell, 2003).

3.4.6 An overview of unique South African features in water resources modelling

The most important issue investigated and discussed in this Chapter is that South Africa has several unique characteristics that have to be accounted for in the development and application of water resources simulation models. To incorporate these unique South African characteristics, a model developer or user often has to find appropriate techniques, mathematical formulations, model boundary definitions, model parameters, data, data formats and other model components.

The information presented in this Chapter has shown that South unique characteristics usually mean that most models developed overseas are not readily applicable in the local environment. On the other hand, locally developed models or redeveloped imported models are not appropriate for local use if they do not properly reflect local requirements and natural conditions. Some important characteristics that should be covered by water resources models to improve their appropriateness in South Africa are:

- The NWA (Republic of South Africa, 1998) provides a legal framework for all water resources planning and management as well as the tools that should be used in these processes.
- Regulations and policies, as well as other legal tools such as water licenses, set direct boundaries in water resources models. As an example, modelling tools for planning water use in a catchment should have the correct water use licensing and allocation rules.
- South Africa is signatory to a number of international treaties on shared water systems. The NWA also places high priority on transboundary water commitments. This approach to shared (international) waters has significant implications for water resources models that handle water resources, especially in those cases where water courses cross country boundaries.
- Water management in South Africa is expected to take place at national level and in defined institutions. In future, CMAs will be expected to perform critically important roles, and each CMA will handle water resources planning and management at WMA level. Modelling tools for such an approach must be able to handle high spatial and temporal resolutions.
- The NWA (Republic of South Africa, 1998) calls for increased participation of stakeholders in water resources planning and management. The NWA has generated an increased interest in modelling tools that are suitable for generating outputs for a variety of stakeholders, including the lay public.
- Hydrological data, which are the main driver of water resources planning and management tools, are scarce in South Africa. Hydrological recording gauges are concentrated in high rainfall areas and data records are often patchy and incomplete due to discontinuities in recording processes. In the case of rainfall data, South Africa has approximately one rainfall gauge per 400 km^2. Detailed physical models that rely on very detailed and continuous data are not applicable over most of South Africa.
- Surface water contributes about 85 % of all the water utilised in the country. Groundwater, which contributes the other 15 % is usually utilised as the main source of water in the more arid and semi-arid regions of the country. Water resources modelling tools with a strong surface water component are generally

applicable in the wetter parts of South Africa and are often inappropriate for the arid regions of the country.

- South Africa is characterised by sparsely distributed urban centres with high densities of human population and industry. These centres create very high water demands and large numbers of pollution points that have to be supported by a network of water supply dams, water transfers from distant river systems and complex urban waste water drainage networks. Water resources models should therefore provide for the storage and movement of water across catchments, which has implications on catchment water balances and ecosystem response. Overgrazing and the existence of many densely populated informal settlements with no waste water drainage facilities also present unique hydrological challenges in South Africa.
- Water resources modelling requires a great deal of expertise in different scientific fields. In South Africa, the numbers of science experts able to address technical issues such as water resources planning and management are dwindling (DST, 2002). As a result, model use by less experienced practitioners is on the increase. Consequently, complicated models that require high levels of expertise and experience are becoming less preferable. User support and training is increasingly becoming more important in water resources planning and management tools.
- While GIS is an essential component of water resources management, (Walsh, 1992), there is a general under-utilisation of this tool in South Africa's water sector. The high cost of GIS packages is blamed as one of the obstacles restricting GIS use. It is therefore important that the models developed for use in South Africa have additional options for users with no access to GIS or are provided with suitable inbuilt GIS tools. The use of free open-source GIS tools is expected to improve GIS use in South Africa as users will tend to avoid the high cost of the commercially marketed GIS packages and select the freely available software.

Chapter 4

Water resources model inputs and pre-processing

4.1 Data and information in water resources modelling

4.1.1 Data capture and accumulation

Data constitute the foundation on which the knowledge of our environment is built. Unfortunately, southern Africa, like many other developing regions, has limited water resources, hydrological and climatological data, with data recording stations being sparsely distributed and in many cases having been closed (Lynch, 2003). The poor quality and distribution of data resources affect the type of modelling tools and the detail that can be accurately accounted for in water resources management and planning models. A number of models that require detailed data inputs such as the MIKE-SHE model (DHI, 2000), a distributed physical model, have little application in South Africa given the state of our data resources. The tendency is therefore to develop and utilise less detailed models and work towards building the data resources to ensure that the country will have adequate data in future. Decisions on the data characteristics have to be considered as part of many interrelated variables. These interrelated variables include: the nature of the water problem to be solved through modelling, the models available, expertise of modellers, data quality and availability, as well as the stakeholder expectations on the overall solutions to the water problem.

Water practitioners in water resources management and planning should ensure that the database developed for modelling processes, covers data in the following areas:

- Hydrological variables
- Soils
- Catchment demarcations and spatial information
- Legal instruments, policies and water infrastructure operation rules

- Water quality
- Groundwater variables
- Water storage systems and their characteristics
- Water demand and land uses
- Biota and abiotic aspects of the watercourses
- Results from previous water management studies
- Identified scenarios and stakeholder expectations
- Available resources for solving the water resources problem
- Water systems and linkages
- Watercourse and flow generation hydraulics
- Water transfer systems and their characteristics

Often, large amounts of data are gathered for specific projects without making provisions for how these data should be archived for later use. Ideally, data capturing and accumulation should have a long-term objective and should seek to store such data where they can be accessed by other users. The information contained in a robust data-management system is then available, not only for the use for which the data were collected originally, but also for a multitude of uses that may never have been anticipated. The NWA (Republic of South Africa, 1998) makes specific provision for the establishment of national information systems on water resources. DWAF must ensure that all water resources project clients and contractors integrate their data capturing and storage efforts with the national initiatives at all times. The need for national information management systems and the guidelines developed by the national body (DWAF) which was tasked, through the Water Act, to develop these data and information management systems, will in future provide the national guidance to all stakeholders who are involved in data generation and archiving.

Water resources models require larger databases when GIS is incorporated. The use of object-oriented databases with relational tables is one approach that is widely recommended (McKinney *et al.,* 1999). Polhill *et al.* (2002) also noted that the use of a relational modelling structure in the database allows for the possibility to vary the simulation scales in a single model, thus allowing detailed high resolution simulations as well as large-scale assessments within one water resources model. Database developers in water resources should clearly consider the implications of the various database architecture selection options to ensure that the final database is technically sound and appropriate to the project needs. Ideally the water resources database should:

- Be compatible with national initiatives in the water sector;
- Incorporate the preferred local and international data inventory trends;
- Allow for transparent linkages between data and the model; and
- Have an ability to statistically integrate and display uncertainties in spatial and temporal representations.

With large water resources databases, water resources modelling is faced with the problem of selecting the most appropriate data components. Winiwarter and Schimak (2002) pointed out that in the past model data inputs were limited by computing power but recent technological improvements have addressed the computer limitations. Rather, the problem centres on complexities of identifying and limiting data inputs to those data with the highest quality. However, these input data limits should not compromise the quality of model outputs, for example if they are applied beyond reasonable limits.

4.1.2 Data quality and formats

The use of a single set of high quality data by all users is a very important aspect of water resources management and planning which can directly eliminate unnecessary inconsistencies. Garry (2002) pointed out that efficiency and effectiveness regarding availability of information to business is enhanced by the existence of a "single version of the truth" across functions and disciplines as a one stop service to water stakeholders in different fields and at a variety of levels in the data and information hierarchy. Newman (2004), however, advised that, after establishing a "single version of the truth" in data management, the challenge remains that stakeholders have to be empowered, so that they share a common view of this truth, thus insuring acceptability and use of the recommended "truth".

For each water resources problem, as much data as possible, especially the latest data should be identified and utilised in water resources modelling to give comprehensive and up to date solutions. However, exceptions, do exist. As an example, modellers may seek to compare outputs generated using the same data after changing model variables, in which case they will use the same old data inputs as those which were used in the previous study.

Local streamflow and water quality records are intermittent, irregular, and frequently contain periods of low accuracy observations. Modellers should note that streamflows and pollution loads are some of the only empirical clues to the true responsiveness of the catchment to rainfall and human impacts. Ideally, systematic efforts have to be made to re-process incomplete or low-accuracy flow records, to patch missing parts of flow records in plausible ways and to infill irregular water quality samples in a systematic manner. There is also a need to ensure that water quality constituents expressed as a monthly time series are calculated in a representative flow-weighted manner.

The presentation of data and their formatting affects what can be done with them, the choice of model, and compatibility of tools that will be required to access the data. The use of uniform standards to format and present data is an important component of accessible data. Samadi, Beukes and Remmelzwaal (2002) pointed out that data communication on a national and international platform based on a rigorous set of standards provides a common basis for all modelling and improves the applicability of performance measurement in model outputs. Any initiative to develop local data resources should account for present and possible future requirements to include such data in a common platform for the country and, ultimately, internationally.

Water resources data capturing and archiving should incorporate the associated meta-data, commonly referred to as “data-about-data”. The meta-data should at least include the following where applicable:

- Recording institution,
- Methods of data collection used,
- Details of data monitoring programme/project in which data were collected,
- Relevant prevailing characteristics when data were collected,
- Processing done and tools used,

- Calibration details,
- Accuracy and range of measurement device and
- Details of modifications made including procedures used.

The absence of meta-data introduces low confidence in data users as they have to deal with the unknown risk of using the data. Additional challenges are also introduced in the modelling process as more attention must be paid to data and model verification, which increases project costs.

4.1.3 Water resources data transmission

The maintenance of agreed standards is important in water resources data collection and transmission. The World Meteorological Organization (WMO) recommended a set of standards to be adhered to when transmitting climate and hydrological data (WMO, 1994). These standards relate mostly to the data transmission formats, where codes are suggested to ensure uniformity and reliability of data transmission. The WMO codes were developed to meet the requirements for the exchange of meteorological data at basin, national and international level, and also to allow the data to be routed over the World Weather Watch telecommunications channels (WMO, 1994). Water resources practitioners should ensure consistent use of standards in data transmission to reduce data errors and reduce modelling risk levels.

4.1.4 Record length and scales

The length of time series hydrological data should adequately cover a wide range of hydro-meteorological events. DWAF (2001c) pointed out that 15 years represents an adequate minimum period for monthly streamflow simulation and, for daily streamflows, 10 years is recommended as a minimum. WMO (1994) also recommend that the basic recording gauges should be operated for relatively long periods of at least ten years. The length of period selected in water resources time series data should ideally cover all possible hydrological or climatic events within a water system, which are usually longer than the 10 to 15 year periods stated above as a minimum.

4.1.5 When to update a set of time series data

Updating of time series data is ideally done as soon as new data become available. However, this is time consuming and may not add value to the modelling process if the new records do not include new events that will improve the decisions made using the data. The internet has drastically improved the processes involved in updating time series data making the process time efficient. In cases where monthly data stretching over at least fifteen years are used, the user can update the inputs once every year. In the case where the available monthly data series are still less than the required fifteen years, data updates should be done more frequently to incorporate changes in each month. In the case of daily data, monthly updates should be preferred for any data sequences that are longer than ten years. For shorter records, daily updates will be very useful. Smaller time steps such as hourly data usually stretch over short periods of not longer than a few months or a couple of years. Users of such data are advised to use all the available data in their water resources modelling processes.

4.1.6 Model data input

The development of input data should ideally start with the development of suitable databases and data formats. Data, information collection and archiving should be structured in a way that enables easy utilization in the targeted model. Resources are wasted in cases where each data user has to format data before use. The conceptualisation of data input routines in water resources models should account for all of the readily available data formats to reduce the burden of converting data from one format to another. While the reduction of non-core activities in modelling such as data formatting have to be minimised, water practitioners are reminded to evaluate the benefits of developing data collection and capturing methods to suit specific tools.

4.1.7 Data review and analysis

Data quality controls should ideally begin at the data collection point such that primary data comply with high quality standards before they are given to users. A system of quality monitoring through inspections should be developed for all data recording stations.

Preliminary data review for data that are collected manually should ideally ensure completeness and correctness of the information supplied with the data. This information includes dates of collection, station name, station identification code as well as checking the completeness of the data and any calculations made by the observer. Checking the observed data against existing records is also recommended to highlight possible hidden inconsistencies.

Preliminary data review is usually followed by the use of specialist software and other simple computer based data assessments. The WMO guide to climatological practices (WMO, 2000) recommends ideal methods to be followed in assessing data. One important computer-based method for checking correctness of recorded elements involves the use of various mathematical relationships such as double mass plots, variability, variance, correlation, consistency. The use of more sophisticated software, especially in the key water resources inputs such as rainfall data, to plot station positions, together with their records to later interpolate data in space and then plot isolines, is recommended in cases where at least three data recording stations are available.

Even after taking stringent measures to ensure data completeness, missing and incomplete records as well as suspicious records are often found within the data-set. Missing records may be interpolated, estimated and patched in. It is important that all the estimated and interpolated values are indicated as such to ensure that users are adequately informed about the data prior to use. A description of the method used to estimate or interpolate missing data will also provide a reliable basis for the modelling process. Other errors and observations noted and resolved should also be recorded using meta-data codes or descriptions.

Preliminary data review should preferably be followed by a data validation process. In validation, standard checks are carried out on the data to detect errors in time and magnitude. Sequential readings or records are validated in the light of expected patterns or the simulated behaviour of related variables that have also been recorded. This assessment should result in the observer applying quality codes to the records indicating if the records are good quality, or faulty, and the level of confidence attached to them in terms of data accuracy. WMO (1994) pointed out that validation processes should never be completely fully automated but should be guided by experienced human judgement to avoid systematic errors in the automated process.

4.1.8 Data coding

Water resources management data requires coding to aid data processing as well as make the files more compact and less ambiguous. Consideration of existing national and international coding systems is important when deciding on a methodology to code data. Coding instructions and training should be made available to observers. The coding method selected should be suitable for further data use, including its use in models. The following is a listing of possible codes to be incorporated with the data:

- Location code (to indicate the place of recording)
- Variable/parameter code (The range of variable codes is enormous and includes: text definition of variable, and letters to represent other information about the data such as measurement units)
- Data-qualification codes (to qualify unusual or uncertain data. This code should also address current and background status of the data.)
- Missing data codes (to indicate data that were not recorded)
- Transmission codes (to ensure data are transmitted quickly and reliably)

4.2 Data processing

Poch (2002) pointed out that original raw data are often defective, requiring a number of pre-processing procedures before they can be registered in an understandable and interpretable way. WMO (1994) explained that data processing entailed transforming the raw data into forms that enable ready manipulation and efficient storage for prospective users.

Data processing involves several processes. Water resources managers have to ensure that the data utilised in their work are at least subject to the following data processes:

- Data preparation (data entry and coding)
- Data entry (input of data into electronic formats for immediate use or archiving)
- Validation (range checks, sum checks, consistency checks)
- Primary processing (standardisation of units, further data coding and data formatting)
- Database updating (adding data to existing databases by extending time series records)
- Secondary processing (data statistical summaries, routine reports, missing data infilling and interpolation)
- Retrieval processes (data and output device selection based on parameter type, location and period of record)
- Output processes (computer storage media, telemetry and plotting)

4.3 Data storage and dissemination

The present trend in water resources management is to build water resources databases that are linked to geographical information systems and modelling tools, which utilise the data. The water manager tasked with the development of the water management database should identify and comply with the initiatives on the national information systems on water resources provided for in the NWA (Republic of South Africa, 1998). DWAF is currently developing the basis for the national water resources information management systems which are discussed in DWAF (2003a).

Other important considerations in data storage and dissemination include the following:

- Identification of the data to be stored,
- Identification of data accumulation and dissemination methods,
- Development of data standards, formats and a data management plan in collaboration with the national processes,
- Definition of meta-data standards and development of a meta-data catalogue,
- Definition of intellectual property rights, confidentiality and other legal boundaries such as data exploitation exclusivity rights,

- Selection of the correct storage platforms with adequate storage facilities and a suitable storage and retrieval engine,
- Ensuring that the data storage and dissemination process allows easy data updates with software to track changes made during updates,
- Development of efficient and adequate dissemination processes which are made available to all users, with ease and at low cost,
- Compatibility with data use requirements,
- Ease of access by targeted users at all times and provision of appropriate restrictions for non-users,
- Development of a strategy for long-term data management,
- Development of quality assurance procedures,
- Installation of functional query handling processes and
- Installation of well maintained data and information computer backup systems.

4.4 Implications of data sources in WRM models

Available data and the data sources have major implications on the selection of modelling tools. The main data component of water resources models, rainfall, is usually available as point measurements from rainfall gauges but its application usually requires spatial representation. As a result rainfall representation in models remains one of the major challenges contributing to poorer model outputs. Alternative sources of data have to be considered depending on the intended accuracy levels in the models, the availability of other data sources and other constraints related to the sourcing of data from such sources. In the case of sourcing rainfall data, the following additional sources need consideration:

- *RADAR:* This has the advantage of giving spatial measurements, though availability is still very limited in South Africa. RADAR data are also prone to RADAR measurement errors which require more resources to resolve than the errors in rain gauge data.
- *Remote Sensing*: In South Africa, data from polar-orbiting satellites are often used in water resources. These data are not continuous as they are measured for a limited time when the satellite being used passes over a particular area. As an example

Landsat-7, provides data for each point on earth every 16 days. Polar-orbiting satellites, which are located closer to the earth (500 km-1500 km) than geostationary satellites (35,000 km) give better spatial resolution (30 m X 30 m resolution) and wider coverage (Dozier, 2003). The procurement of satellite data and its processing are expensive for most local water resources studies. Water practitioners are recommended to take advantage of recent initiatives in the Department of Agriculture which have made the data from the Landsat-7 Satellite freely available. Landsat images, including the archives that date back to 1986 are now freely available to all governments, research organisations and non-governmental organisations in SADC as a result of the South African Department of Agriculture's commitment to provide twelve million Rands towards procuring these data images (NDA, 2004).

The processing of data to provide a better representation of the study area, such as converting point data to give data series that can be applied over a defined catchment area, involves a number of possible techniques. Some techniques which water practitioners should take into consideration when dealing with rainfall data are as follows:

- *Inverse distance weighting*: weights are calculated depending on the distance between the location where an estimate is required and the locations where the rainfall is measured. However, this method is limited in that it never produces a rainfall value which is higher than the maximum value in the observed data-sets. This is not realistic.

- *Interpolation:* a mathematical relationship of surrounding point values with the area where aerial or point values are required is established and used to generate the required time series data. One such method, Kriging, utilises the covariance structure of the area where an estimate is required.

- *Multiple regression:* This method requires a sufficient spatial density of the locations at which the values are observed to explain the variation in the measured amounts. The method is most useful in mean annual precipitation estimations.

- *Stochastic generation*: The method generates synthetic data after establishing important statistics pertaining to the observed data for the different sites and preserving these statistics in the generated data estimates. The method can generate data series that are longer than available records; this is useful when long hydrological sequences are required in a water resources modelling scenario.

4.5 Summary of recommendations on model inputs and pre-processing

Water resources models are driven by data and , unfortunately, South Africa has limited hydrological and climatological data. The available records are characterised by sparse aerial coverages, poor quality, discontinuities in time, and unstructured data collection and archiving initiatives. Continuity of collection of time series data has been affected by the country's ongoing political transition where national priorities which targeted improvements in livelihoods and poverty alleviation have affected investments in data collection projects (Gill, 2004). The type, resolution and accuracy of modelling tools that can be successfully applied to any area are almost entirely dependent on the nature of available data. In the water resources simulation case study used in this research, a monthly hydrological modelling approach was selected rather than a daily approach that could have provided more detailed assessments, as this was the best resolution that could be used with the available data. In this case study, it was observed that the case study area, which exceeded 3 000 km^2 had only four reliable rainfall gauges and two runoff gauges. This sparse distribution of rainfall gauging points means that detailed physical models are not generally applicable in most catchments.

Apart from land-based recording gauges, other available sources of data have to be considered especially for the purposes of providing more reliable data. Here, data from remote sensing and radar technology are of particular importance. These forms of data are expected to become more widely applied and accepted in the future of Africa's water resources management (NDA, 2004). The development of tools for water resources management should seek to utilise remote sensing and radar data where appropriate.

The absence of a nationally supported and coordinated Earth Sciences data collection and archiving programme has meant that water resources data are not readily available. Water resources management projects need additional inputs to collate, process and format data in most water resources projects. Data secured from one project, must still be checked for quality and processing as there are no guarantees or applicable national standards on water resources data quality and data processing. The choice of tools used in providing information to decision making is limited by the state of the available data and the additional resources required to process these data. The process of data collection, updating, formatting, archiving, review, analysis, coding and dissemination should ideally be done according to nationally and internationally recognised standards. Important international guidance is provided in WMO (1994). On the local scale, direction will soon become available through the NWA-based initiatives (DWAF, 2002a).

Chapter 5

Model software selection and development

5.1 Policies and a framework in development and use of models

The NWA (Republic of South Africa, 1998) is often described as an "enabling" piece of legislation. While this Act provides little in the way of specific regulatory procedures, it does stipulate the types of standards and tools that should be used for integrated water management approaches, as emphasised in the National Water Policy (DWAF, 1997d), and this provides a platform for flexibility. The strength of this approach is that it enables the flexibility that is required in regulating the dynamic water sector. In spite of the National Water Act being enabling, the framework for the integrated management of water resources is adequately provided for via water resources strategies. At national level, the Act provides for the Minister to progressively develop a NWRS. This strategy must set out the objectives, plans, guidelines and procedures relating to the protection, use, development, conservation, management and control of water resources (DWAF, 2002a). Further provisions have been made in the NWA to develop IWRM on a catchment basis using the WMA units. This provision requires the formulation of water resources management strategies at WMA. The CMAs are expected to develop Catchment Management Strategies (CMSs) within each declared WMA. The establishment of common water resources approaches and techniques that will be guided by DWAF's national tools is ideally the key to the success of the 19 CMAs. Some of the main goals used by DWAF to provide providing common guidelines to CMAs include the following:

- To assist CMAs to adopt a consistent, technically sound and dependable approach to the evaluation of water resources for compulsory licensing,
- To assist in developing understanding of the scientific and technical information requirements of water resources management and,

- To provide a common basis for the assessment of modelling outputs from different stakeholders working in different WMAs as well as different water management institutions.

Modelling results from one area are often compared or related to findings from other areas. This immediately calls for the use of common definitions to variables and parameters. Typical cases include modelling scenarios which utilise vegetation characteristics. In South Africa, the Acocks vegetation definitions (Acocks, 1988) have been used as the baseline in model inputs. The Acocks vegetation water use data are currently considered very coarse for representing water use by different types of vegetation at spatial resolutions below the level of quaternary catchment. Data on water use values by different plants are currently being improved using field-based techniques such as those using large aperture scintillometer (LAS) methods (Dye and Le Maitre, 2004). Vegetation water use should therefore be derived on the basis of all the available field data including the LAS measurements as well as other historical definitions such as the Acocks system.

The definition of low flows in WRM models, where water flow regimes are model inputs or impact on other inputs, is often a source of discrepancies in deriving a common base in the simulations. An important assessment of methods for defining Low Flows in South Africa was presented by Smakhtin, Watkins, Hughes and Sami (1998) who identified the following software-based methods for low flow analysis:

- Flow duration curve construction (The method should be used in conjunction with the interactive facility to determine the flow rate and the percentage of time that this rate is equalled or exceeded).
- Analysis of continuous low-flow intervals and their deficient-flow volumes (The method looks at events/spell or continuous time series analysis).
- Extreme low flow events frequency analysis.
- Procedure to separate base flow from the total continuous daily stream flow hydrograph, and to estimate related base flow characteristics.
- Procedure to calculate recession characteristics of a stream (recession constant, half-flow period, distribution of recession rates).

DWAF is working towards the development of standards to guide model developers in their software coding. Model developers working on DWAF projects are expected to follow these coding standards in their modelling processes (DWAF, 2002b). Most other water institutions, water resources researchers, and consultants do not have any software standards and usually recommend that their contractors comply with DWAF's standards.

DWAF, through the Planning Directorate, has set up a system to define some of the most important boundaries in model selection, through a process of model accreditation. In this initiative, water resources management models are evaluated and recommendations are made as to which models should be used for national water management and planning projects (DWAF, 2003c). A national advisory committee to "police" the process of model selection for DWAF water resources projects is still to be set up.

International trends also have a major bearing on local modelling frameworks. McKinney *et al.* (1999) reported that general water quality simulation capability is now a standard feature of river basin models. River basin water assessments in South Africa are now expected to integrate groundwater, surface water and water quality issues into the main modelling components, without the sorts of bias in one or more areas as was usually the case in previous studies. Most previous studies on surface water resources failed to adequately account for groundwater, and in some cases groundwater was treated simply as a percentage loss to the water system; this is clearly not a correct representation of the complex groundwater processes or the hydrological cycle (WRC, 2003a).

Water management policies in arid and semi-arid countries, seldom are able to use catchment or river basin based water resources management approaches. These approaches are not suitable in arid areas which seek to address groundwater with its own demarcation boundaries such as aquifer boundaries (Moriarty, Batchelor and van Wijk, 2001). Moriarty *et al.* (2001) also noted that the optimisation models used in South Africa usually exclude groundwater. This is unfortunate since groundwater provides a significant contribution to water supply. In fact, groundwater currently contributes more than 15 % of all water supplies that are used in South Africa which is an important component of the water balances used in water resources modelling. The NWA promotes a holistic and integrated approach to water resources management and it is therefore essential that groundwater should be adequately addressed in all modelling efforts. If groundwater is excluded in modelling, data on groundwater are never collected and modelling routines remain undeveloped. The exclusion of groundwater in basin models provides a poor basis for further work on the total water system or on groundwater specifically.

The water resources management conceptual framework is the foundation of model development and should be updated continuously as water management trends change. This includes changes in the types of technology and software that can be used. In cases where relative locations of areas being modelled and other referral spatial points are involved, the modeller should ensure that a GIS is incorporated in the water management model. The use of Digital Elevation Models (DEMs) is also becoming increasingly important in all water resources projects where more accurate and accessible terrain data are required, and which naturally give a platform for better model outputs. The changing water environment, such as reduced water availability, increased demands for water, and the ever growing concerns on deteriorating environmental qualities including general natural resources quality, has seen a significant demand for policy reform. McKinney *et al.* (1999) pointed out that in spite of all the changes in policy, most water management tools still fail to answer questions on feasibility, costs and the likely implications of alternative water management policies in developing countries. Improved understanding of the different variables in developing countries will result in the development of more applicable modelling tools.

Davis and Hirji (2003) pointed out that the development of models should take place within an environment that accounts for stakeholder needs, especially those who are targeted to use the tools or gain from their use. Without such interaction with stakeholders, modelling tools are likely to fail to gain acceptance, which is crucial for their usefulness to be fully realised.

5.2 Topography, watercourses and climatic factors in South Africa

Topography: Water resources modelling is sensitive to the topographical characteristics of the study area. The topography directly influences water flow regimes, runoff distribution, temperatures, wind speeds and directions, rainfall types and intensities as well as many other water resources variables. The mostly mountainous coastal areas of South Africa have very sharp difference in rainfall patterns over short distances. Hilly terrain with relatively high rainfall patterns reaching annual levels above 1000 mm are common in the south eastern coastal areas of South Africa while a generally flatter terrain with drier conditions where annual rainfall is below 500 mm, cover 65 % of the country; in other words: most of the inland area. A large portion of South Africa, 21 % of the land area, is very arid with annual rainfall below 200 mm. Model settings and parameter values will need to be modified for each river basin under consideration as most river basins have dissimilar climatic and topographic characteristics. The use of high resolution and accurate DEMs is recommended to ensure that the topography is accurately and completely represented in water resources models.

River systems: South Africa's water demand is concentrated in relatively few locations and rising water demands in these areas has already or will soon exceed the water available in surrounding catchments. A system of water transfers from distant catchments is utilised to meet the excess demand in areas of high water demand. McKinney *et al.* (1999) observed that the complexity of the water transfers in South Africa requires more resources to be invested in the modelling of integrated water systems rather than the separate component approach that has characterised local water studies in the past. Water practitioners should appreciate the linkages of water system components across the different boundaries to be able to provide dependable and reliable models.

The classification of river systems according to resource quality objectives followed by a process to determine and provide for the basic human needs and ecological reserves (Republic of South Africa, 1998), are key variables that should be accounted for in the development and use of water resources models.

Climate: Water resources modelling in South Africa has to account accurately for the country's unique climatic characteristics. In South Africa, the main driver of water resources model, rainfall, is highly unpredictable, and accurate estimations of rainfall are complicated by the sparse distribution of rainfall gauging points. Large fluctuations in the average annual precipitation are very common in most areas of the country. Some 21 % of the country receives a total annual rainfall of less than 200 mm, 48 % of the country receives between 200 mm and 600 mm, while only about 30 % of the country records more than 600 mm. In total, 65 % of the country has an annual rainfall of less than 500 mm - usually regarded as the absolute minimum for successful dry-land farming. With such differences in rainfall the use of average hydrological data inputs is usually a major source of errors in the water resources planning and management models. A maximum limit of one rainfall gauge per 25 km^2 is provided for daily models such as the ACRU model (Seed *et al.,* 1995).

Most modelling data, especially rainfall, are available from several organisations and more resources are usually needed to acquire and format these data before any modelling can start. Important data sources that have to be consulted for water resources simulation assignments include: the Department of Water Affairs, SAWS, the Agricultural Research Council (ARC), Hydrology and soils research groups - especially the CSIR and University of Natal, Agricultural land users - especially the South African Sugar Association (SASA) and a large number of town councils and municipalities.

Continuous, smaller time step data such as hourly data and, to a large extent daily data, are seldom available. Modellers are advised to thoroughly investigate model data requirements and the available data before they select or develop a specific model for use. While the tendency in the water sector has been to use models that do not require detailed inputs, the introduction of water management and planning at WMA level (Republic of South Africa, 1998) has meant that the preferred monthly models will be too coarse for the temporal and spatial scales required. The NWA, with its CMA-based planning and operational management, requires modelling and decision making to be made at smaller scales in both time and space to accommodate the daily operations at field or plot scales.

Landuse and vegetation: The vegetation mapping and research in South Africa's water resources management is usually based on the research and work conducted by the botanist J. P. H. Acocks (Acocks, 1988). The Acocks vegetation database has been used as the basis for simulating land cover in South Africa (Lumsden, Jewitt and Schulze, 2003). Modellers should take note of the results of recent field-based research to determine water use by vegetation, using techniques such as the Bowen Ratio Energy Balance Systems and the Large Aperture Scintiliometer (LAS) (Dye and Le Maitre, 2004). These techniques are expected to improve the accuracy of vegetation water use model coefficients as well as other model inputs related to energy fluxes over different land uses.

Soils: The targeted level of accuracy and resolution as well as available resources are some of the key factors to be considered when deciding on the types of soils data to use in the modelling process. An important local source of soils data for water resources modelling is the soils classification developed for the South African version of the SCS model (Schmidt and Schulze, 1987). Schmidt and Schulze (1987) classified South African soils according to their hydrological responses to suit the requirements of the SCS model. The SCS model gives a scale of 1 to 100 for the classification of soils according to curve numbers that describe the soil on the basis of antecedent soil moisture conditions and its ability to absorb water.

South African soils information inventories include the BNHSZ inventory where the country's soils were mapped into 84 Broad Natural Homogenous Soils Zones (BNHSZ) (Schulze, 1996). This soils inventory is coarse and useful for regional parameterisation. Schulze (1996) also presented drainage rates indices, plant available water; soils texture classes and soils depths for different areas in South Africa. This data is however too coarse when one is using higher resolution models such as those simulating field scales.

An internationally accepted method of defining soils that should also be considered is the Global Soil and Terrain (SOTER) database. The SOTER database incorporates soils data from all corners of the world presented in a single database that is characterised by a single set of rules using reference keys based on the *'soil characteristics', 'soil properties' and 'soil horizons'*(FAO, 1995). In South Africa, water resources modellers should aim to define soil characteristics in their models in a way that follows local and international standards. Van Huyssteen and du Preez (2004) have recently provided some detailed insights into some local soils characteristics in relation to the SOTER database. The use of internationally accepted standards including those in soils is crucial for model reliability and acceptance as it provides a platform for current and future reference with other local, regional and international research.

Groundwater: With more than 15 % of all water use in South Africa being supplied from groundwater, the groundwater–surface water interactions must be considered as important components of the water balance in water resources models. Water practitioners should note that they introduce weaknesses and inaccuracies in water resources models if they inadequately represent the complex nature of any constituent components of the water resources system, including both surface water and groundwater processes.

5.3 Water resources institutional frameworks in South Africa

DWAF is the primary water resources institution in South Africa. This department has made provisions for new approaches in the water sector through the application of the NWA (Republic of South Africa, 1998). The approaches provided for in the NWA require water management tools that are suitable for higher resolution water assessments and planning to be implemented through CMAs, as well as the existing larger-scale water assessment and planning methods at river basin level. Apart from the challenges encountered in developing a framework for delegating water resources management and planning activities to CMAs, DWAF is also faced with the challenge of integrating all stakeholders and involving them in decision making and solution developments within their WMAs (Merrey, 2000; Schreiner and van Koppen, 2000; Moriarty *et al.,* 2001;). Merrey (2000) also noted that the majority of the people within catchments are mostly poor urban or rural communities who are unaware of the provisions of the new water law and the CMA process, and are often left out of the initiatives to develop the CMAs. Water practitioners must appreciate the risks involved in developing solutions for water resources problems in an environment of transformation where the long-term goals remain largely undefined or poorly understood. It is important to ensure that all affected parties are involved and take ownership of the decisions and solutions.

While the WMA approach is based on river catchments, water resources managers must realise that the catchment approach is not always logical in arid areas such as the Karoo in South Africa. Arid areas usually depend on groundwater resources whose boundaries do not always coincide with surface catchment boundaries. Moriarty *et al.* (2001) noted that in such arid areas, the focus should be on managing water at the lowest appropriate levels using IWRM principles such as aiming to maximise the economic value of water, rather than simply applying catchment-based approaches.

5.4 Socio-economic, political and trans-boundary issues

5.4.1 Socio-economic issues in modelling

A holistic approach in water resources management requires the incorporation of socio-economic factors in the management tools. Freebairn (2004) explained that water has a variety of values, for example, either directly in household drinking, bathing and gardens, or it is a valuable input used in helping to grow irrigated vegetables, rice and cotton or as environmental flows to sustain native flora and fauna. Because of its scarcity, allocating more water to one use, say industry, means that less water is available for other uses such as the environment. This calls for the application of all inclusive decision making processes which involve the evaluation of all the advantages and disadvantages in water resources planning and management decision making.

In water resources management in an arid country, the inclusion of economic considerations should account for the allocation and reallocation of limited water volumes among the competing uses so as to increase economic efficiency and national well being. Economic efficiency, or national productivity, is maximised by allocating water among the different uses so that the marginal social value of the last litre used in each different use is equalised (Freebairn, 2004). In South Africa, in addition to efficiency, economic management of limited water must also consider equity and poverty alleviation issues. Schreiner and van Koppen (2000) pointed out that the concept of water as an economic good should never be considered in isolation from other social costs as this will cause considerable cost to society through societal issues such as water deprivation that is aggravated by inequities. Good water resources planning should be robust in the sense of being able to understand present scenarios and address future changes in the availability of water, market conditions, technology, incomes, equity and resource quality objectives, particularly where many of these changes cannot easily be forecasted. Modelling tools must be able to accommodate the inevitable changes in the water resources variables which take place over time.

5.4.2 Political issues in WRM

Water management takes place within the framework of a political environment that is also guided by the water legislation and other statutory instruments such as water policies and regulations. Bate and Tren (2003) reported that the allocation of water in South Africa has been used as a political weapon in pre-independence South Africa. The attachment of land rights to water licenses was one measure that resulted in major discrepancies in water allocations that were meant to support the politics of the time. The water allocation discrepancies are further aggravated by the skewed spatial and temporal distribution of water when expressed against the spatial distribution of human population and water needs. High population densities in South Africa are located far from adequate water resources. These population density patterns have tend to follow the distribution of economic resources such as minerals and the forced settlement patterns of previous political regimes. The challenge to water practitioners is to ensure that they can account for water outside of the boundaries set by the political framework. This will involve cases such as the integrated consideration of water systems for previous homelands and other connected systems, and applying equitable water allocation rules while addressing the differences in data availability and quality as well as major knowledge gaps.

Since independence in 1994, South Africa has shifted from the more Euro-centric water legislation based on riparian rights and replaced it with the NWA, which is more suitable for the new democracy and also suits the semi-arid conditions over most of South Africa. While every effort has been made by the legislators to define new approaches to water management, the water resources manager is left with the challenge of translating the legal instruments into real life practices. The tendency to take existing tools and apply them without adequately addressing the new legal requirements in the water sector hampers compliance with the spirit and content of the legislation. Ideally, water managers should seek to develop permanent solutions; this includes the development of new water resources planning and management tools that are suitable for the new water environment.

5.4.3 Trans-boundary issues

Integrated water resources management requires a holistic approach that covers all stakeholders and all components of the water system being investigated. Since most watersheds cross administrative and political boundaries, modellers have to ensure that the tools they develop or use are not constrained by unnatural boundaries such as country or other administrative borders. The NWA makes provision for water to meet international obligations as one of the two most highly prioritised allocations of water; the other important allocation being water for the basic human needs and ecological reserve. South Africa is also signatory to a number of international legal instruments on shared water courses. These legal instruments include water specific tools such as the Revised SADC Protocol on Shared Watercourse Systems (SADC, 2001) and the Helsinki rules (ILA, 1996) and instruments addressing a wide range of sustainability issues including water such as Agenda 21 (UNCED, 1992). South Africa also has other bi- and multi-lateral treaties and other targeted international agreements with its neighbouring countries to cater for the detailed requirements of specific water systems, such as the Lesotho Highlands, the Limpopo Basin and the Orange River System.

In water resources systems that affect different stakeholders who are separated by administrative boundaries, models must reflect the affected parties' perspective of their water resources system. The water resources models should allow different stakeholders to understand model assumptions, content, capabilities and output, have confidence in the model's validity, and view it as a useful decision support tool. A model developed within these characteristics presents a "shared vision" which is an important characteristic of successful water resources models involving transboundary decisions, and indeed any other decision involving different stakeholders.

The management of water resources within the SADC region under the Revised SADC Protocol on Shared Watercourse Systems should observe a number of principles (SADC, 2001). Ideally, the principles that should be accounted for in the case of model-based water resources management should include the following:

- Respect for the sovereignty of member states in the utilisation of a shared watercourse.
- Application of rules of general or customary international law and equitable utilisation.
- Maintaining a proper balance between development and environment protection and conservation.
- Co-operation on joint projects and studies.
- Information and data sharing.
- Equitable and reasonable utilisation of shared watercourse systems.
- Use of discharge and abstraction permits or licences.
- Obligation to notify neighbouring countries about emergency situations, protection against pollution and use of installations for peaceful purposes.

The principle on information and data sharing is very important in water resources modelling. It is aimed at levelling the playing field and creating an enabling environment for negotiations for equitable utilisation of shared watercourses. The SADC Hydrological Cycle Observing Systems (SADC-HYCOS) was developed to address this principle (Mokuoane, 2000). Information sharing is central to the co-operation and economic integration envisaged by the SADC Treaty. The development of water resources models for the SADC region is expected to strengthen co-operation and information sharing within the SADC countries (SADC, 2003a).

More detailed water management requirements within SADC are expected to be handled by a water sector coordination unit which was established under the original SADC Protocol (SADC, 2001). Its vision is: To attain the sustainable, integrated planning, development, utilisation and management of water resources that contribute to the attainment of SADC's overall objective of an integrated regional economy on the basis of balance, equity and mutual benefit for all member states.

The water sector unit's overall objective is to promote co-operation on all water matters in the SADC region for the sustainable and equitable development, utilisation and management of water resources, and contribute towards the uplifting of the quality of life of the people of SADC region. Water resources management initiatives that cross SADC country boundaries, including modelling have to be formulated within the framework of the revised SADC Protocol on Shared Watercourse Systems.

5.5 Recommendations on models and software

Due to the complexity and variability of factors affecting water resources planning and management, data observations alone are often insufficient for decision making; hence the need to use models. Models are recommended for use as tools for a wide range of tasks which include: to compensate for the lack of measured data, to simplify the complexity of the mostly unpredictable interaction of water resources variables, and to assess the implications of possible water resource management scenarios.

The decision to use a model must be based on a sound understanding of the problems to be solved. Schulze (1998) reported that a number of problems occur where models are used to solve problems that do not warrant the use of such tools. Simple discussions and consultations, supported by good data, can easily provide many solutions. Many water resources managers are confronted with the need to decide on the use and selection of suitable modelling tools. A decision to use a model should be guided by the following:

- Complexity of the problem and the number of dependent variables and fixed parameters,
- Presence of uncertainties or situations involving approximate knowledge where predictions are difficult,
- Presence of conflicting goals and the need to incorporate several viewpoints or options,
- Cases where multiple scales need to be evaluated,

- The need to evaluate many scenarios,
- Problems where distinct boundaries of prevailing phenomena cannot be established,
- Decision-making situations that require the use of long sequences of data,
- The need to provide multi-objective outputs,
- Problems involving complex relationships, including those where such relationships are continuously changing such as weather and climate.

The decision to use a model has to be made with a clear understanding of the available resources, including data and tools or the expertise required for solution development. As a minimum requirement, the decision on which model to develop or select should fall within the following guidelines:

a) *What decisions are to be made using the model outputs?* Models can be developed to answer a specific question pertaining to a unique problem, for example flow regime problems on a river supplying water to a specific hydropower station, will require a customised model. Other scientists believe that the idea of developing specific models to answer specific questions is expensive and time consuming. Parkinson (2003) suggests that developers must focus more on developing general modelling solutions that can be used to answer many questions. The advantages of having one proven model ready to answer a variety of questions is that time can be spent more efficiently on simulating and analysing outputs rather than devoting this time to endless model developments. McKinney *et al.* (1999) identified the differences between "holistic" and "specific" models. Holistic models are data-intensive and may involve many other processes that a model user may not need to simulate but ends up simulating because he cannot run the model without those processes. "Specific" models were identified as less comprehensive and less demanding in terms of setting up and running. Ideally, modellers should weigh the benefits of each choice of modelling approach to determine whether or not a specific or a general model are most appropriate to the problems to be solved.

b) *What is the best model resolution (spatial and temporal scales) to address these problems?* Model choices are passively or actively made on the basis of the concept of control volume using the relationship between the complexity of the mathematical equations and the spatio-temporal resolutions involved. The very detailed scales, for example a two metre wide water course require the use of complex equations in hydrodynamic models, whilst larger spatial scales, for example, areas which are as large as the physical system with sparse data would be adequately addressed using rules of thumb. Khatibi, Moore, Booij, Cadman and Boyce. (2002) categorised modelling techniques using the concept of control volume. Figure 5.1 below shows the model categorisation based on the control volume technique.

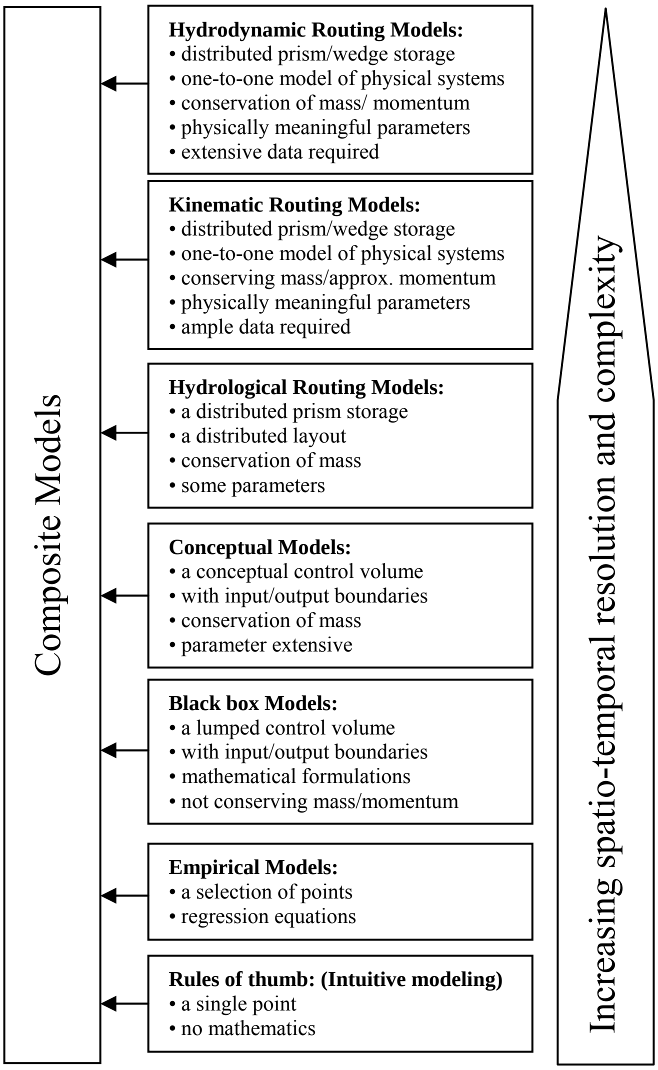


Figure 5.1 Categorising modelling techniques (Adapted from Khatibi *et al.*, 2002).

National water resources planning in South Africa has tended to use conceptual models run at monthly time steps with the quaternaries as the smallest area units. The limitations in available data have also meant that stochastic hydrological time series data are used instead of the mostly short and patchy records. The NWA however makes provision for more detailed water resources studies at WMA level. The WMA approach has generated a need to evaluate water use at field level and plan daily water operations as well as implementing non-permanent water use licenses that seek to enhance water use efficiency. Ideally these higher resolution objectives will best be handled using physical models that give more accurate and detailed catchment characterisation.

c) *What objectives are to be met?* The most appropriate model to meet the project objectives must have an optimal balance between uncertainties resulting from model assumptions (or fundamental uncertainties), and uncertainties resulting from the data (or operational uncertainties) (Willems, 2003).

d) *What are the model costs? Do these costs cover model support?* Availability of model user support, model user-friendliness, the costs of procuring the model as well as model version control requirements are other considerations to make when evaluating model costs. Many internationally developed models require high levels of expenditure on licences and continuous model updates. Model users are required to renew their licenses annually or more frequently than that to be able to continue using such tools. In most cases users are not supplied with the model source code so that they never have a chance to customise the tools or connect these to other modelling tools. Backward compatibility is a major problem in some commercially developed software where users are forced to purchase frequent releases of new model versions and updates.

e) *How accurate and reliable are the inputs?* When errors dominate in say the distributed rainfall inputs, a simpler (lumped or conceptual) model can provide more robust water resources simulations. (Khatibi *et al.*, 2002) pointed out that process descriptions alone do not compensate for shortfalls in the data and vice-versa. When rainfall data are made available through a dense gauging network generating high quality data, the more detailed distributed grid type or physical model may be used to provide improved output performance.

f) *What are the quality and confidence levels expected in outputs?* Models generating high margins of errors are usually unsuitable in cases involving economics and financial investments as well as other cases where very low levels of risk in water availability are required. Low risk levels for water availability are required in industries of a national strategic nature such as hydropower stations or other highly prioritised users such as transboundary commitments. "Holistic" models that combine different objectives such as economics and hydrology face challenges in sub-model output quality differences caused by complexities in handling information exchange between the sub-models. While hydrologic models often use simulation techniques, economic models usually use optimization techniques. The two sub-models often have different spatial development horizons, which refer to the area over which the impacts and developments extend, as well as the area over which the model can be validated. Time horizons are also different, with economic models using large time horizons spanning years, while hydrologic processes use small time intervals that reflect physical processes. Water practitioners should aim to utilise object-oriented programming combined with relational databases to capture the scale hierarchies in economic-hydrologic models.

g) *How complex should the model be?* In rainfall-runoff models, simple models that involve fewer parameters or weights to be evaluated, and which rely on simple mathematical procedures (e.g. least squares solution), are often better able to forecast discharge than those models which involve a significantly higher number of parameters or weights to be evaluated and which rely on complex mathematical computations (Goswami, O'Connor and Shamseldin, 2002). However, simple models pose the risk of errors of exclusion or over-simplification and they may overlook important factors. A process of value management is required which would reveal that a further reduction in the number of variables or level of detail in model components would create an unacceptable difference between the model and the real system where model output is distinctly unrelated to the physical system characteristics.

h) *Which models are accredited?* National model accreditation processes such as those being implemented by DWAF have major implications on the models available for use in DWAF projects. In DWAF's model accreditation system, models to be used on specified types of studies were identified and evaluated for use in these areas. Recommendations were then provided to modellers on which models to use, when, and how to use them (DWAF, 2003c). These recommendations tended to prefer models that the selecting teams were familiar with, which is a source of undue limitations to the promotion of innovation and allowing rapid developments that are important for the sustainability and continued acceptance of modelling tools and their outputs.

In cases where a new model has to be developed, the model developer is expected to design the model development process. The model development process should be guided by the following:

- The level of expertise available to develop or run the model. In the case of developing models for CMAs, one must appreciate the level of skills of the CMA personnel who will be tasked to use the model. Many models developed and used in South Africa have little to no user support and, in some cases, the models are too complex for a user community that is inadequately trained and supported (Hughes *et al.*, 2004).
- Ideally, model development processes need to be standardized on best practice. DWAF is currently establishing a system of guidance to modellers. This will involve the development of guiding documentation which will be recommended by an advisory committee.
- Models should be sufficiently detailed to capture the dominant processes and natural variability, but should not be unnecessarily refined as this compromises the computation time and wastes resources (Booij, 2003). The model developer must first identify the dominant processes and associated key variables. Second, the appropriate spatial and temporal scales for each key variable are determined. Furthermore, relationships between key variable scales and the output variable are used to combine the appropriate variable scales to one appropriate model scale. In the third step, mathematical process descriptions consistent with these model scales are selected or formulated.
- The model developer and users must have a common or “shared vision” in the model. The ownership of a model will need to be transferred to the stakeholders and the model users through carefully planned engagement during the model development process.

5.6 Routines, objects, tool integration and interfacing in modelling

Effective integration of data sources, numerical tools, application of intelligence analysis and knowledge are the key to good water resources modelling. At the level of data and background-information collation, numerous and often incompatible bits of information from disparate sources have to be brought together. Ideally, model development should be structured to incorporate integration early in the development stages.

McKinney *et al.* (1999) recommended that modelling at basin level should ideally be based on a GIS decision support system that integrates economic, agronomic, institutional, and hydrologic components. To achieve this, comprehensive modelling frameworks that integrate agronomic, institutional, and hydrologic components need to be developed at basin level. This will facilitate the national provision of policy instruments, national economic assessments of water use as well as hydrological assessments. Figure 5.2 below presents a suggested framework for river basin management modelling, including relationships, and decision items at various levels.

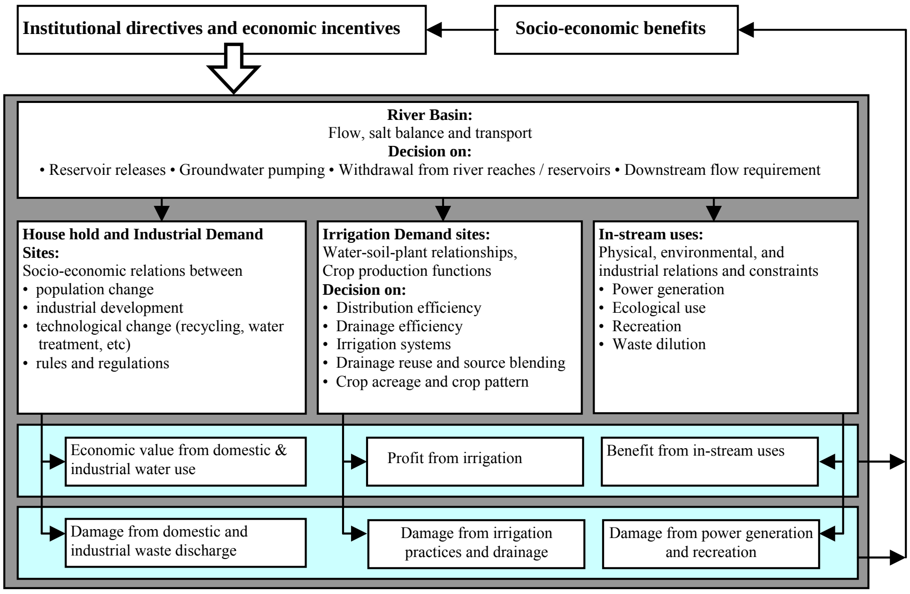


Figure 5.2 Framework for river basin management modelling (Adapted from Mckinney *et al.*, 1999).

Model developers and water managers should appreciate that water resources models tend to become components of water resources decision support systems through the integration of data components, simulation routines, multi-criteria decision aids, as well as GIS and DEMs capabilities. Ideally, the approaches followed in model development should allow parallel integration rather than sequential connectivity/integration. Sequential integration involves a unidirectional linkage of routines and sub-models such that outputs from each component are fed as input into a subsequent component. This process was common in early modelling practices and does not allow the more realistic bidirectional interactions between the various system components (McKinney *et al.*, 1999). Integrating the model components in a parallel way allows status information to be exchanged between the sub models continuously during simulation, such that feedback loops and external linkages are updated as the simulation progresses. Sequential integration will usually give flawed results in water resources modelling where backward linkages and external influences occur with time (McKinney *et al.*, 1999).

Standardization of the databases has to be addressed as a key aspect of integrated models. The goal is to provide an environment in which all computations made from different modelling components from a variety of institutions with similar data inputs but simulating different aspects of water resources modelling, converge and share the same data resources. The overall goal should be to establish a consistent and always realistic representation and comprehensive database for the river network, its critical reaches, water transfer routes, water sources, pollution points, water storages and operation rules, climate, landuse, topography, water provision scenarios and other water resources variables (Pistocchi and Mazzoli, 2002).

The representation of multi-spatial scales in water resources models is best handled using agent-based models where object-oriented programming is combined with a relational database (Polhill, Gotts and Law, 2002). This approach allows user-configurable scale hierarchies to be enabled using a relational model, where relational tables are used to link the groups of entities (spaces) at different levels of detail. While this method is a flexible approach to the representation of the various scales at which processes influence land use changes and how land uses at a variety of scales influence model parameters, the method results in reduced flexibility on how the objects can be redefined at run time. Any changes to the modelling objects will require the changes to be reflected at the different scales.

5.7 User platforms and model packaging

Model users tend to prefer models that present model platforms and user interfaces which blend well with their existing software functionalities and working environment (Eric, 1999). It is also easier to integrate models and other applications if they were developed using the same source code or have a similar architecture such as an object-oriented approach. A model should at least emulate (have the same "feel and touch") the commonly used platforms for existing tools to improve user acceptance and reduce training needs. Another important approach in the development of user platforms or model working environments is to create user profiles with different privileges and responsibilities in the interaction with the water resources management tools. This will lead to the definition of different levels of interaction between the user and the models, thus reducing user support requirements and improving model security and integrity.

The use of **h**yper **t**ext **m**ark-up **l**anguage (HTML) and e**x**tended **m**ark-up **l**anguage (XML) files in user platforms to support model users will ensure that the documentation of a user defined model exactly matches its implementation. Discrepancies are commonly encountered between the description of a model and its actual implementation, leading to inconsistencies in the model building processes. South African model users frequently encounter such discrepancies when they attempt to use the WRPM, WRSM90 and Shell models with updated input data. The documentation is usually inadequate for one to be able to determine how the different model components were connected and the correct source data including information on how they were manipulated to give the revised data used in the model. The recommended approach is to incorporate software into the model for automatic documentation of the model development process, inputs and simulation information. In this automated document, changes are automatically tracked, recorded and stored each time a user modifies or adds anything to the existing model.

The use of an open data model is important in improving user access. The user will be able to access such data using other external software and can easily integrate these data into their reports. A web browser can also be used to access input and output data stored in an open model.

5.8 Guiding thoughts on model software selection and development

The NWA (Republic of South Africa, 1998) as well as the National Water Resources Strategy (DWAF, 2002a) make provision for monitoring and information systems for water resources and set responsibilities for providing water related information. In these provisions, general boundaries to areas and issues that can be handled by water resources models are provided. Chapter 5.1 of this study unpacks the national legal and policy provisions to make them useful to a model developer.

The efficiency and effectiveness of water resources model applications are influenced by the topography, watercourse systems and climatic variables. On the other hand, how the water resources model handles socio-economic, political and trans-boundary issues influence the softer issues in modelling such as model acceptance by stakeholders and even the technical correctness of the solutions derived from the model. It follows, then that, the prescription of models or their development should ideally account for all the variables which affect the output, acceptance of outputs and applicability of derived solutions. The application of model results is usually left to water institutions. Chapter 5.3 also discusses the constraints within these institutions, their capacities and preferences which have to be accounted for in the model development or selection.

As part of the model development or selection a series of questions should be asked to determine the most appropriate solution. These questions include the following:

- What are the problems to be solved using the model?
- What is the best model resolution (spatial and temporal scales) to address these problems?
- What objectives are to be met?
- What are the model costs in terms of licences, copyrights and user support

- What are the input requirements?
- How complete, accurate and reliable are the available input data?
- What is the level of expertise available to run the model and to receive as well as to evaluate model outputs?
- How complex should the model be?
- Are there any models or model components already prescribed or preferred to handle the problem?

These questions should be addressed in such a way that the model development process generates a surplus of benefits and meets the set objectives as well as complying with the requirements of relevant water resources projects. One of the key modelling requirements is to generate reasonably accurate results that can be defended inline with the existing legislation, such as the NWA in South Africa and transboundary legal instruments in cases where international waters are involved.

The development of water resources models that use stochastic data or remotely sensed data is an important approach in most of South Africa's drier catchments where data availability is very limited. Detailed physical models that require high-resolution data should be restricted to small data-rich catchments. In the absence of other specific recommendations, the 25km^2 aerial unit size recommended for the ACRU model's driver rainfall approach (Seed *et al*, 1995) should be used as the maximum size of each sub-catchment unit to be simulated separately.

Water resources model development and use in recent years has focused on tools that are useful in national planning. The WMA approach required in the NWA looks at the WMA as the largest spatial unit such that new tools should now seek to simulate catchments at higher spatial and temporal resolutions.

The globalisation of sustainability and development issues as provided for in initiatives such as the global Millennium Development Goals, as well as the enactment of enabling national legislation such as the NWA in South Africa, have brought about new challenges to water managers, thus increasing the complexity of existing water resources problems. Political boundaries are no longer expected to be the limit of water resources management and planning programmes. Water resources managers are now expected to ensure that the water resources management and planning tools in use are holistic and incorporate issues beyond the political, regional, socio-economic or other boundaries which do not coincide with hydrological or water management boundaries.

Model development, like any other part of information technology, is very dynamic. The use of MS-DOS text commands that dominated earlier models is no longer a preferred option. Many new users coming out of colleges and universities have no training on older IT tools such as MS-DOS. On the other hand, the component model approach or OOP has meant that modellers do not have to reinvent many model components as they can now use existing components developed by other specialists in their own space and time for specialised functions in their own modelling tools. A lot of these components are freely available and allow for full third party interfacing and use. The Internet has also revolutionised model user support and development. Modelling tools developed today should ideally take advantage of the Internet functionalities, to provide remote user support, online feedback and further model development, WWW-based model dissemination and user support through online forums, as well as WWW based output presentation and publishing of results. Presently, there are no strict restrictions on the material that is posted on the internet. Model developers are expected to go through the process of peer-reviewing and ensuring high quality levels in their internet postings. On the other hand users of internet based modelling material should ideally exercise caution.

Chapter 6

Verification, Calibration and Validation

6.1 Model Verification

Once a model is developed the numerical techniques in the computer code will need to be examined to ascertain that they are accurate representations of what is being modelled, the concepts involved, the optimisation methods applied, as well as the relations between variables. These model examinations constitute model verification. Most model coding software comes with debugging applications to identify and suggest solutions for some model code inaccuracies. Modellers should ideally make full use of debugging software to handle shortcomings in the coding and model equations, as well as numerical discrepancies.

Model verification should ideally utilise actual input data. DWAF (2001c) recommends that the data used in model verification should at least display a representative range of events to be simulated. Further recommendations in DWAF (2001c) are that verification should attempt to capture all the model efficiency parameters handled in calibration but may utilise shorter time series data than those used in calibration. Verification inadequacies should be handled early in the modelling process, ideally as part of the model development, in which case model equations can be improved. In model verification, adequate examination of the mass balances and flow routing can resolve most of the model coding shortcomings.

In some cases, additional model verification is done as part of the modelling process, preferably after model calibration. In such cases, if the verification is not acceptable according to a defined set of criteria, then a second round of calibration is required which should account for the lessons learnt from the verification. This should be followed by a second round of verification. If the model was developed to allow model improvements through repetitive verification and calibration, the cyclic repetitions should continue until the model parameters are "acceptable". Acceptability will mean that the simulated values "mimic" as closely as possible corresponding observed values either in a time series or for individual discrete events/output.

6.2 Model Calibration / Validation

Model calibration and validation are essential steps in any water resources model application. During calibration, model parameters, for which data may not be available, are estimated and adjusted until the model outputs are equal to or relate closely to recorded or observed measurements. Calibration simply involves adjusting parameters in the model so that the model reproduces the measurements. Calibration should involve iterative procedures of parameter evaluation and refinement, as a result of comparing simulated and observed values of interest. However the values of the calibration parameters must be within a range that makes sense to the physics, chemistry or other scientific principles involved. Model validation is in reality an extension of the calibration process (Donigian, 2001). Its purpose is to assure that the calibrated model properly assesses all the variables and conditions which can affect model results, and demonstrate the ability to predict field observations accurately for periods separate from the calibration effort. By definition, model validation involves the comparison of model results with numerical data that have been derived independently, either from experiments or observations of the environment.

6.2.1 Observed and field data in model calibration

Model efficiency and the accuracy of the calibration process are highly dependent on the available observed data. Identifying abnormalities in the observed data should be the first step of the calibration and validation processes. Calibration in water resources models should ideally include comparisons of daily, monthly and annual values as well as individual events, whenever sufficient data are available for these comparisons. All of these comparisons should be performed for a proper calibration of hydrology and water quality parameters. In addition, when a continuous observed record is available, such as for streamflow, simulated and observed values should be analyzed on a frequency basis and their resulting cumulative distributions (e.g. flow duration curves) compared to assess the model behaviour and agreement over the full range of observations.

Ideally, modellers should always utilise the latest available data in model calibration. In cases where current sources differ from those used in other to-be-compared studies, the modeller should illustrate and examine the differences by using a data-set that is common to both sets of analysis. Seeking such common ground between comparative analysis facilitates the understanding of differences and similarities in model outcomes and findings, which improves the interpretation of model outputs (DWAF, 2001c).

In recognition of the inherent variability in natural systems and often unavoidable errors in field data observations, water practitioners should ideally establish and use data accuracy characterisations that are consistent in water resources management. In cases where specific local guidance on characterisation of accuracy in data is not available, international documented characteristics may be used. Important documented characteristics include those from the United States Geological Survey (USGS), which provided the following characterization of the accuracy of its streamflow records in all its surface water data reports (Donigian, 2001):

Excellent Rating	95 % of daily discharges are within 5 % of the true value
Good Rating	95 % of daily discharges are within 10 % of the true value
Fair Rating	95 % of daily discharges are within 15 % of the true value

The WMO Commission for Hydrology also provides recommendations for accuracy levels in hydrological simulations as presented in Table 6.1 below.

Records that do not meet these accuracy criteria are rated as ‘poor’ and water practitioners are cautioned against their use. According to Donigian (2001), model results for flow simulations that are within the accuracy tolerances indicated above can be considered acceptable calibration and validation results, since these levels of uncertainty are inherent in the observed data.

Table 6.1 Recommended accuracy (uncertainty levels) expressed at the 95 % confidence interval (Adopted from WMO, 1994).

Measured parameter	**Accuracy**
Precipitation (amount and form)	3-7 %
Rainfall intensity	1 mm per hour
Evaporation (point)	2-5 % or 0.5 mm
Wind speed	0.5 m/s
Surface water level	10-20 mm
Wave height	10 %
Water depth	0.1 m or 2 %
Width of water surface	0.5 %
Velocity of flow	2 – 5 %
Discharge	5 %
Suspended sediment concentration	10 %
Suspended sediment transport	10 %
Bed-load transport	25 %
Water Temperature	0.1 - 0.5 ^{o}C
Dissolved Oxygen	3 %
Turbidity	5 – 10 %
Colour	5 %
pH	0.05-0.1 pH unit
Electrical conductivity	5%
Soil moisture	1 kg/m^3 - 20 kg/m^3

In the calibration of time series routines, the observed data and simulated data should attempt to cover all the possible scenarios of climatic conditions, hydrological systems, anthropogenic conditions and other important variables depending on the objectives of the modelling. DWAF (2001c) recommends that calibration should be based on at least 10 years of data for daily time steps, and at least 15 years for monthly steps, in order to evaluate parameters under a variety of climatic, soil moisture, and water quality conditions. Generally, the longer the record, the better the quality of simulation outputs. The selection of a suitable record length should be considered in relation to rainfall variability. Semi-arid areas and mountainous areas, which experience high rainfall variability, are better represented by longer rainfall record lengths (Seed *et al.*, 1995).

6.2.2 Model parameters in calibration

Calibration focuses on determining the most suitable values and ranges for model parameters. A number of methods are available for determining the parameter values.

Automatic methods or optimisation techniques such as the use of genetic algorithms and the shuffled complex methods are some of the many techniques that modellers can use. In the absence of better techniques, modellers are expected to use their own judgement based on experience and existing literature to estimate model parameters. In water resources models at basin scale, modellers should ideally follow a three step process in selecting parameters. In the first step, key hydrological parameters are determined; the next step should involve sensitivity analysis of the parameters to come up with an optimal parameter set. In the third step the parameters should be regionalised to derive specific parameters for each sub-basin.

Model parameters that cannot be deterministically, and uniquely, evaluated from topographic, climatic, physical, chemical or other scientific characteristics of the watershed and compounds of interest may require other parameter estimation techniques such as automatic calibration. A number of software tools are available for automated parameter estimation. Modellers must however be aware of the limitations of the automatic method selected. Most automated calibration methods do not capture all the dependent variables, they often fail to appreciate the parameter sensitivities and users cannot easily comprehend the processes involved in these methods. It is therefore advisable to use either manual calibration alone or automatic calibration together with manual methods. Some automatic calibration methods based on the genetic algorithm can adequately replace manual calibration (Ndiritu and Daniell, 1999). Ultimately, calibration should result in parameter values that give the best overall agreement between simulated and observed values throughout the calibration period.

6.2.3 Model objective functions

The objective functions or criteria selected to evaluate model performance must be relevant to the project objectives or decisions to be made using the model. The performance measurement criteria used in water resources modelling are often referred to as objective functions.

In South Africa, DWAF (2001c) recommends that the minimum criteria for goodness-of-fit of the simulated values when compared to recorded values should at least address the limits in the following:

- Annual mean, standard deviation, dry season mean (streamflows, constituent concentrations and loads),
- Percentile curve (streamflows, constituent concentrations and loads),
- Mean monthly distribution (streamflows, constituent concentrations and loads),
- Cumulative mass curves,
- Gross yield-storage curve for streamflows, and
- Deficient flow-duration frequency curves.

The NWA (Republic of South Africa, 1998) makes provision for a number of objective functions in water resources modelling. In the water ecosystem area, the NWA provisions include the classification of water resources and resource quality objectives, water reserve provisions and pollution prevention targets. In Chapter 4, of the NWA (Republic of South Africa, 1998) provisions for water use are presented to cover issues such as permissible water use, equitable and beneficial water allocation, water use authorisations and licences, lawful water use, controlled water use activities and water use allocation schedules. These legal requirements should be accounted for in setting out the model boundaries as well as in the definition of objective functions where appropriate.

Model calibration/validation usually involves statistical and graphical comparisons of model outputs with actual observed or measured data. Schulze (1998) pointed out that visual comparisons of model results are very subjective. Donigian (2001) pointed out that in water resources management models which involve water quality routines and biotic constituents, model performance should preferably be measured using, primarily, visual and graphical presentations rather than the frequency of observed data which is often inadequate for accurate statistical measures. The use of statistical measures is usually recommended where adequate data are available. In this case, predetermined criteria of goodness of fit in the objective functions are established. Some of the main statistical measures or objective functions in the rainfall runoff component of water resources modelling include the following:

Conservation of the mean (Ob$\bar{x}$): This is expressed as the percentage difference between means of observed and of simulated values. For a good simulation this objective function has to be minimised, zero being the ideal level.

$$Ob\bar{x} = 100.\frac{1}{N}\left(\sum_{i=1}^{N} Q_{obs,i} - Q_{sim,i}\right) \qquad \text{Equation} \quad 6.1$$

Overall volume error (F): For best results *F* has to be minimised.

$$F = \sum_{i=1}^{N}(Q_{obs,i}\Delta t - Q_{sim,i}\Delta t) \qquad \text{Equation} \quad 6.2$$

Root mean square error (RMSE): The closer the RMSE is to zero the better the simulation.

$$RMSE = \left(\frac{1}{N}\sum_{i=1}^{N}(Q_{obs,i} - Q_{sim,i})^2 \right)^{\frac{1}{2}} \qquad \text{Equation} \quad 6.3$$

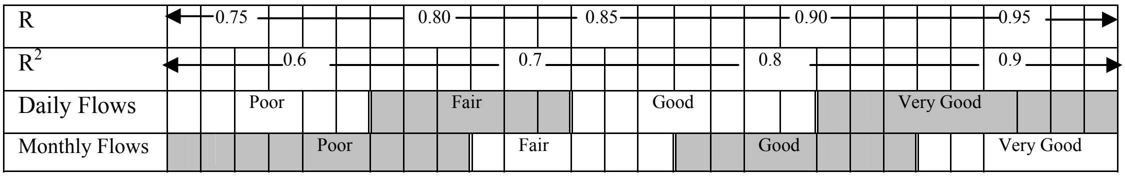
Coefficient of regression (R^2):

$$R^2 = \frac{\frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2 - \frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs,i} - Q_{sim,i}\right)^2}{\frac{1}{N}\sum_{i=1}^{N}\left(Q_{obs,i} - \overline{Q_{obs}}\right)^2} \qquad \text{Equation} \quad 6.4$$

The coefficient of regression, measures the degree of association between the simulated values and the values estimated by the regression model. This objective has to be maximised to 1 for a good simulation.

As a guide, Table 6.2 below presents an example of the criteria recommended when using the coefficients of regression values (R and R^2) for water flow comparisons in the United States' Environmental Protection Agency (EPA) projects (EPA, 2003).

Table 6.2 Comparisons of coefficients of regression values (R and R^2) for water flow (adopted from EPA, 2003)



R	0.75	0.80	0.85	0.90	0.95
R^2	0.6	0.7	0.8	0.9	
Daily Flows	Poor	Fair	Good	Very Good	
Monthly Flows	Poor	Fair	Good	Very Good	

Nash and Sutcliffe (1970) recommended another important objective function for the measurement of efficiency in Rainfall-Runoff models. Equation 6.5 presents the "Nash and Sutcliffe" objective function equation; the aim is to generate a simulation where the values of *E* is very close to one. Values of *E* above 0.7 are classified as acceptable.

$$E = 1 - \frac{\sum_i (Q_{sim_i} - Q_{obs_i})^2}{\sum_i (Q_{obs_i} - \overline{Q_{obs}})^2} \qquad \text{Equation} \quad 6.5$$

Where Q_{sim} is the simulated streamflow, Q_{obs} is the measured streamflow and $\overline{Q_{obs}}$ the average streamflow value in the measured period.

In monthly and annual simulations the EPA also recommends some rough guidance for calibration/ validation targets as shown in Table 6.3 below:

Table 6.3 Calibration/ Validation targets in environmental modelling (Redrawn from EPA, 2003)

Criteria	% difference between simulated and recorded values		
	Very Good	**Good**	**Fair**
Hydrology / Monthly Flow	<10	10-15	15-25
Sediment	<20	20-30	30-45
Water temperature	<7	8-12	13-18
Water Quality/ Nutrients	<15	15-25	25-35
Pesticides/ Toxics	<20	20-30	30-40

6.2.4 Guidelines for effective model calibration

The United States Geological Survey provides additional recommendations on guidelines for the calibration of water resources models (USGS, 1998). These guidelines have been adapted and presented in Table 6.4 below, where guidelines pertaining to specific U. S models such as the model MODFLOWP have been excluded. Model calibration guidelines, such as these (Table 6.4) are not intended to be followed sequentially, but may be repeated many times during model calibration. Ideally, modellers should use their own judgement of their modelling objectives to select those guides which provide the best relationship with their specific modelling scenario.

Table 6.4 Guidelines for effective model calibration. (Adapted from USGS, 1998).

Guideline	Description
1. Apply the principle of parsimony	Start simple and add complexity as warranted by the hydrogeology and the inability of the model to reproduce observations.
2. Use a broad range of information to constrain the problem	For example, in ground-water model calibration, use hydrology and hydrogeology to identify likely spatial and temporal structure in, for example, aerial recharge and hydraulic conductivity, and use this structure to limit the number of parameters needed to represent the system. Do not add features to the model to attain model fit if they contradict other information about the system.
3. Maintain a well-posed, comprehensive regression problem	a) Define parameters based upon their need to represent the system, within the constraint that the regression remains well-posed. Accomplish this using composite scaled sensitivities and parameter correlation coefficients. b) Maintain a comprehensive model in which as many aspects of the system as possible are represented by parameters, and as many parameters as possible are estimated simultaneously by regression.
4. Include many kinds of data as observations in the regression	Adding different kinds of data generally provides more information about the system. In ground-water flow model calibration, it is especially important to provide information about flows. Hydraulic heads simply do not contain enough information in many circumstances, as indicated by the frequency with which extreme values of parameter correlation coefficients occur when using only hydraulic heads.
5. Use prior information carefully	a) Begin with no prior information to determine the information content of the observations. b) Insensitive parameters (parameters with small composite scaled sensitivities) can be included in regression using prior information to maintain a well-posed problem, but during calibration it often is advantageous to exclude them from the regression to reduce execution time. c) For sensitive parameters, do not use prior information to make unrealistic optimized parameter values realistic.
6. Encourage convergence by making the model more accurate	Even when composite scaled sensitivities and correlation coefficients indicate that the data provide sufficient information to estimate the defined parameters, nonlinear regression may not converge. Working to make the model represent the system more accurately obviously is beneficial to model development, and generally results in convergence of the nonlinear regression. Use model fit and the sensitivities to determine what to change.
7. Evaluate optimized parameter values	a) Unreasonable estimated parameter values could indicate model error. b) Identify parameter values that are mostly determined based on one or a few observations using dimensionless scaled sensitivities and influence statistics. c) Identify highly correlated parameters.

8. Test alternative models	Better models have three attributes: better fit, weighted residuals that are more randomly distributed, and more realistic optimal parameter values.
9. Evaluate potential new data	Use dimensionless scaled sensitivities, composite scaled sensitivities, parameter correlation coefficients, and one-percent scaled sensitivities. These statistics do not depend on model fit or, therefore, the possible new observed values.
10. Evaluate the potential for additional estimated parameters	Use composite scaled sensitivities and parameter correlation coefficients to identify system characteristics for which the observations contain substantial information. These system characteristics probably can be represented in more detail using additional estimated parameters.
11. Use confidence and prediction intervals to indicate parameter and prediction uncertainty	a) Calculated intervals generally indicate the minimum likely uncertainty. b) Include insensitive and correlated parameters, perhaps using prior information, or test the effect of excluding them. c) Start by using the linear confidence intervals, which can be calculated easily. d) Test model linearity to determine how accurate these intervals are likely to be. e) If needed and as possible, calculate nonlinear intervals f) Calculate prediction intervals to compare measured values to simulated results. g) Calculate simultaneous intervals if multiple values are considered or the value is not completely specified before simulation.
12. Formally reconsider the model calibration from the perspective of the desired predictions	Evaluate all parameters and alternative models relative to the desired predictions using prediction scaled sensitivities, confidence intervals, composite scaled sensitivities, and parameter correlation coefficients.

6.2.5 Selection of model objective functions

Different objective functions are applicable to different models, and to the same models used for different goals. The selection of objective functions should at least be guided by the following:

- Errors between simulated and observed values must be minimal.
- The selected objective functions must be related to the specific aim and relevance of the modelling application.
- The characteristics of the simulations that require the most accurate representation should be accounted for in the objective functions.

- Objective function selection should have a bias towards those objectives that were identified as important by the stakeholders/users as well as those that are important to the problem owners.
- Selected objectives must not conflict with other objectives including those in the sub-models.
- Objective functions should be practical to model and must relate as closely as possible to the physical system.

In the case of the ACRU model, and other similar water resources models in South Africa, Jewitt and Schulze (1999) recommended a selection of objective functions for application. The objective functions in this list and other ACRU related functions are explained in more detail in Schmidt, Smithers, Lynch, Schulze, and Pike. (1995). These authors advised practitioners to, use the ACRU-model based objective function selection, listed below, for local water resources models, where applicable:

- Total observed/simulated flows (mm)
- Mean observed/simulated flows (mm)
- Correlation coefficient
- Students “t” value
- Linear regression coefficient
- Base constant for regression equation
- Standard error of simulated flow
- Variance of observed flow
- Variance of simulated flow
- Standard deviation of observed flow
- Standard deviation of simulated flow
- % difference in standard deviation
- Coefficient of determination
- Coefficient of efficiency

There are different concepts used in objective functions for river basin or water resources models based on the differences in types of models, especially the simulation and optimisation models. In simulation models, the objectives are centred on the evaluation of the water system performance relative to set criteria which include ecological sustainability, climate change implications, changing water demands and water supply prioritisation. In optimisation models, the objective functions are interrelated, with constraints driving the model internal processes. A typical example of constraints used in South Africa is the penalty system in the WRYM and WRPM. Modellers should however note that optimisation models in water resources should also contain a simulation component to characterize the hydrologic regime, unless another method of incorporating the hydrological process is utilised.

An insight in the processes involved in optimisation models such as the WRYM and the WRPM will assist water practitioners in their modelling. These models use the dynamic programming algorithm where the main problem to be solved by the model is decomposed into a sequence of smaller problems ("sub-problems"). A system of interrelated objective functions, utilising a penalty system for solution optimisation are set for the "sub-problems". The model user defined penalty system forces the internal model solutions to follow the route with the least penalties when the model is run. Solutions derived for the "sub-problems" are linked to the overall objective which may be as an example to maximise the yield of a river basin or ensuring consistent water flows in the river throughout the year. In the case of yield maximisations, examples of objectives set in the sub-problems include increasing the water storage potential of individual dams just before the rain season, thus maximising water storage in the upper reaches of the catchment. To maintain a consistent flow regime in the river you may however need to keep higher levels of storage, or operate larger dams with capacities of say four times the mean annual rainfall (MAR) which seldom spill but have enough water to maintain consistent flows. The optimisation of objectives in the WRPM is done using two sets of algorithms:

i) Network Algorithm
ii) Tree Algorithm

The network algorithm which utilises an out-of-kitler routine solves the flows in each channel after the tree algorithm has resolved the outflows at each system node (DWAF, 1987).

In cases where variables are constrained by several issues, the best model choices are usually optimisation models. In a river basin, these models can allow objectives to be set on a variety of water resources issues, which include:

- Hydrologic specifications (e.g. minimum flow levels)
- Social value systems (e.g. river basin stakeholders' choice)
- Economics (e.g. maximize economic return per unit of salinity)
- Equity (e.g. justified free water supply limit)
- Environmental quality (e.g. reserve allocation)

The scale at which problems are intended to be solved in the model influences the type of models to be developed and applied, as well as the objective functions to be used. In most detailed studies such as the simulation of evaporation processes of a small field (e.g field covering one hectare), mechanistic models which simulate the physical processes in detail are preferred. Objective functions for such detailed models should aim at high levels of detail and accuracy. Variables such as water table with accuracies in terms of centimetres, moisture content to millimetre detail, number of plants and their individual species, leaf cover per square metre of area, temperatures and rain water interception per square metre are of critical importance in detailed mechanistic models. On the other hand, modellers working at larger scales such as research projects involved in simulating water availability in southern Africa over the past 100 years will mostly utilise conceptual models where the level of detail and model objectives are coarser. As an example the model inputs may be such that the representations of large spatial areas, for example, thousands of square kilometres of land cover, may be entered in the model in a generalised format as Savannah grassland without giving further details. Objectives set will also have to depict a generalised format that can capture average parameters over thousands of square kilometres.

6.2.6 Stages in water resources model calibration

In water resources management and planning models, the calibration process should be handled as a hierarchical process which begins with the hydrology calibration of both runoff and streamflow. In cases involving water quality and sedimentation, the next stage should be to calibrate the sediment erosion and sediment transport, and finally calibration of non-point source loading rates and water quality constituents. Other hydrologists (Donigian, 2001; EPA, 2003) suggest that when modelling land surface processes, hydrologic calibration must precede sediment and water quality calibration since runoff is the transport mechanism by which non-point pollution occurs. Likewise, adjustments to the in-stream hydraulics simulation must be completed before in-stream sediment and water quality transport and processes are calibrated.

In the hydrologic calibration stage at least five characteristics should be calibrated in successive examinations of the river basin, in the following order: (1) annual water balance, (2) seasonal and monthly flow volumes, (3) water quality, (4) base-flow, and (5) storm events. Simulated and observed values for each characteristic are examined and critical parameters are adjusted to improve or attain acceptable levels. Table 6.2 and Table 6.3 show examples of calibration target levels recommended by the United States of America's Environmental Protection Agency.

Sediment calibration should preferably follow the hydrologic calibration. In sediment calibration, sediment parameters should be modified to increase agreement between simulated and recorded monthly sediment loss, deposition and storm event sediment removal. Estimated loading rates based on measured rates of sediment depositions are also used to calibrate the sedimentation parameters in cases where continuous loading rates have not been measured.

The calibration of water quality and non-point source loading should aim to obtain acceptable levels of agreement for observed and simulated concentrations as well as meeting the agreed criteria. Table 6.2 and Table 6.3 gives some recommendations on water quality calibration targets. The calibration process should ensure that parameters remain within physically realistic bounds, and in the case of non-point source loading, the expected parameter ranges as presented in literature should be used as guidance.

6.3 A summary of guidance on model verification, calibration and validation

In this chapter, model verification, calibration and validation is discussed, with the aim of improving the quality of the modelling process. A key aspect of ensuring high quality outputs in modelling is to verify the numerical techniques in the computer code, thus ascertaining that they are accurate representations of what is being modelled, the concepts involved, the optimisation methods applied, as well as the relations between variables.

A process of calibration and or validation should ideally follow the verification process before the model is finally used. In calibration, the modeller is expected to use the available input records and then enter and adjust the estimated model parameters, for which data may not be available until the model outputs are equal to or relate closely to physical observations. Based on this research, the following are some of the considerations to be made in evaluating the efficiency and accuracy of the calibration process:

- The observations used in calibration and validation must be of appropriate quality. A good rating is recommended for daily flows where 95 % of the daily flows are within 10 % of the true value. Flow records of this level of accuracy are seldom available in South African catchments. As an example, an area exceeding 3 000 km^2 that was used in the case study of this thesis in 2001 to 2003 had only two flow gauges. One of these gauges had incomplete flow records ending in 1988 (Figure 9.6).
- The use of the WMO (1994) guidelines is recommended for the accuracy of variables covered in this document; these are presented in Table 6.1.
- The use of conservation of the mean, overall volume error, root mean square error and coefficient of regression are recommended for use in comparing simulated and recorded flows.
- In calibrating sediment loads and deposition, an accuracy of 20-30 % difference between the simulated and recorded values is recommended. This figure is also recommended as a good accuracy value by EPA (2003).

- On the basis of the investigations in this study, the calibration process should ideally follow the USGS (1998) recommendations (Table 6.4) where project specific guidance are not provided.
- In surface water resources models involving water quality the calibration process should ideally involve the following three calibration stages, carried out in the same order.
  1. Hydrological calibration
  2. Sediment calibration
  3. Water quality calibration

  The above calibration sequence allows for sedimentation processes to utilise calibrated flow and other hydrological data. The water quality calibration is likely to utilise the hydrological data and calibration parameters. Sedimentation which is a sub-component of water quality processes is ideally handled before the overall water quality calibration.

Chapter 7

Spatial data and stakeholder inputs in water resources modelling

7.1 Geographical Information Systems (GIS)

Water resources management and planning problems are always characterised by a spatial dimension. A system to handle the spatial dimension, GIS, is an important component of effective solutions in water resources problems. GIS is a general-purpose technology for handling geographic data in digital form, with the ability to pre-process data into a form that is suitable for problem analysis, to support analysis and modelling directly, and to post-process and present results in a useable and user-friendly format (McKinney *et al*,1999). GIS offers a spatial representation of water resources systems, and it also offers predictive and analytical capacities for solving complex water resources planning and management problems. Bivand and Lucas (1997) observed that GIS is generally classified as a technological tool, while modelling is seen more as a scientific activity and that these different perspectives of GIS and models affect their integration. GIS provides the platform for integrating water resources variables of various modelling aspects, which include hydrological, social, demographic, economic and environmental.

GIS can be used in various ways to support water resources modelling. Some of the uses where GIS can be applied include the following:

- *Store and manage data* – GIS performs geospatial data-management tasks (data storage, manipulation, preparation, and extraction) and spatial data processing (overlays and buffering) (Maidment, 2001).

- *Extract parameters* – GIS provides characteristics and properties of watersheds and river reaches for hydrologic modelling (Maidment, 2001).

- *Provide visualisation* – GIS displays can be used in three modelling stages
    - Pre-processing:- to verify the basic data and information for the model.
    - During modelling:- to visualise physical processes against a time line e.g. flood propagation, pollution flume propagation and sediment loading.
    - Post processing:- for evaluation of the results of the modelling. For example, floodplain mapping in GIS shows the extent of areas damaged by floods (Collins and Campbell, 2003).

- *Documentation support* – GIS provides documentation support for geographic images, mapping, drainage files and meta-data.

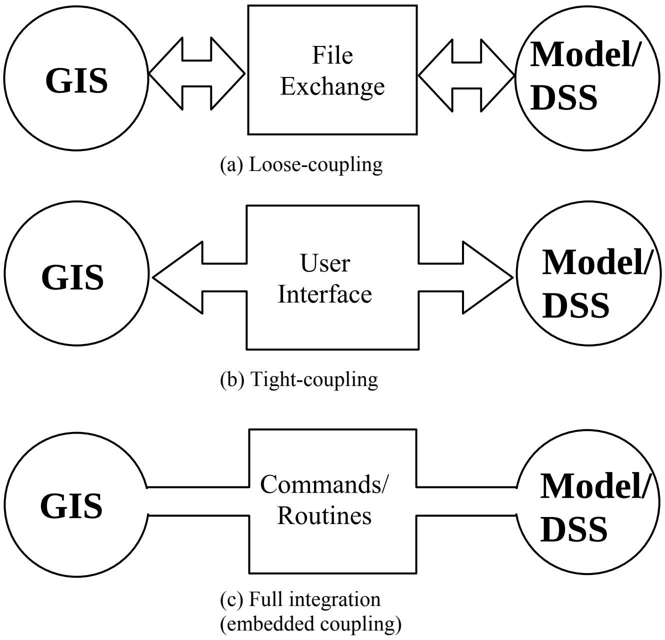
- *Model surfaces* – A GIS can be used as a mapping or terrain analysis tool and for delineation of catchment areas as well as representing channel shapes based on elevation models (Doan, 2003).

- *Develop interfaces* – Map-based interfaces to hydrologic models can be developed using GIS tools (Doan, 2003).

GIS and modelling routines are interfaced using a number of techniques. The lowest level of interfacing is achieved through "loose-coupling", followed by "tight-coupling" and then "full integration" or "embedded coupling". Modellers and stakeholders should have adequate information on the level of interfacing that will give the best results in the different water resources modelling projects. Jun (2000) and McKinney *et al.* (1999) provided some basic characteristics of the different levels of interfacing which can be used as guidance in water resources modelling projects. Figure 7.1 illustrates the integration classifications presented by Jun (2000).

"Loose-coupling" is the simplest approach where two systems exchange files such that a GIS uses data from the other modelling system as its input data, and vice-versa. At this level of integration, the two systems run independently and no system modification or programming takes place except that the data or outputs of one system need to be formatted for use as inputs to the other system. The GIS processes in "loose-coupling" are separated from the main model such that they use a separate database with information being transferred between the GIS and the main water resources model (McKinney *et al.*,1999). "Loose-coupling" does not involve coding or other complicated handling of source code of the two systems being linked.

In "tight-coupling" the two systems share the communication files as well as a common user-interface. The development of the common user interface is achieved by using macro languages such as Arc Macro Language (AML) which is provided by the Arc/Info GIS package. This approach can also support minimal numerical manipulations since AML is not suited to perform complex numerical manipulations. The two systems however still remain separate.



(a) Loose-coupling

(b) Tight-coupling

(c) Full integration (embedded coupling)

Figure 7.1 **Schematic classification of GIS-integration methods in terms of the extent of integration (Adapted from Jun, 2000).**

Techniques that result in "tight-coupling", thus producing an integrated system where the GIS routines and other model routines share the same database, do not require the availability of the source code or an in-depth understanding of the GIS code. These techniques are less demanding in programming and are accessible to most modellers. Djokic and Maidment (1993) recommended that the best method to achieve "tight-coupling" is to use an application programming interface (API). In an API for GIS, a library of routines allows the user to access and integrate most of the functional capacities of the GIS in a standard programming language; this allows the user to write analytical programs, which, through the API functions, directly handle spatial data management, graphic display, and user interaction. Another important technique for “tight-” or “deep-” coupling is the use of object-oriented programming which was recommended by Raper and Livingstone (1996).

The idea behind the use of object-oriented programming is that a river basin is perceived as consisting of objects that interact in specific ways. In the river basin the coupling will involve spatial objects and thematic objects. Spatial objects represent real world entities, and thematic objects include attributes, methods and topics. The attributes include spatial, external physical, environmental and socio-economic data related to the spatial objects, the methods are the rules or functions describing the relationships between the objects, while the topics represent the objectives or tasks to be reached or completed.

In the most complex form of coupling, embedded coupling or full integration, a more complete integration can be achieved by creating user-specified routines through generic programming languages such as FORTRAN or C and adding them into the existing set of commands or routines of the GIS package. This requires such resources as source codes or command libraries and relatively complicated programming, which is not available to most GIS users.

Jun (2000) recommends that if resources permit, users should apply embedded coupling which gives the best results through ease of operation, facilitating quick achievement of modelling objectives. He further pointed out that embedded coupling is less error prone as data transfers are not done and has the added ability of looking at both the spatial system and the environmental system as one. Bivand and Lucas (1997) also explained that full integration gives better, faster, easier systems and enhanced water resources analysis. However modules should not be so tightly integrated that the potential universality of the design is seriously reduced.

The tendency to build the best model to represent the physical processes in reality, and then worry about finding data that would fit into that model should be avoided. Modellers should first identify the data and then build a spatial hydrological model that uses the data that are actually available or can be obtained within the project boundaries.

GIS integration is therefore expected to address input data requirements and the specific roles of GIS in the modelling.

The selection of a GIS coupling technique in South Africa should be guided by a number of issues which include the following:

- The GIS procurement costs including the licences of the GIS components and source code to the model developers and users. As an example a complete GIS package (Arc-GIS) costs more than R193,000 (GIMS, 2003) which most water resources practitioners in South Africa find unaffordable.
- Availability of adequate skills in the developer team to address short-term needs during development and the long-term demands of maintaining the water resources model and its GIS components.
- Data availability and the formats of existing GIS data. Most projects in South Africa tend to utilise the digitised, relatively coarse 1:50,000 maps in GIS. These input data are major constraints in GIS integration. Efforts to develop complete integration of the water resources model and GIS may not add value in cases with poor input data, such that "loose-coupling" will be the most appropriate approach. In cases where continuous DTMs are available covering the whole study area, it will be important to consider full integration.
- Availability of associated software for use with the GIS applications. As an example, most GIS users in South Africa are using ESRI GIS software, however these users usually lack the Arc-Objects and other modules required for integrating this type of GIS software with models. In many cases they have licences for limited functionality of the GIS package thus limiting the possibilities of how the GIS integration can be handled.
- The final modelling output presentation requirements, targeted audience expectations and the preferred model packaging and distribution.

Water resources practitioners should ideally seek to identify ways to address the challenges of integration when developing solutions to water resources management and planning problems. Some of the ideal requirements of an integrated system of water resources modelling and GIS include the following:

- All GIS data must be held in a common geospatial coordinate system,
- The primary structure used for spatial representation of large regions must be vector data (points, lines, and areas), supported by raster and Triangular Irregular Network (TIN) surface data where necessary,
- Correct and complete datasets in suitable formats must be available,
- Relationships among geographic features in different data layers are needed to trace water movement from feature to feature through the landscape, and
- Geospatial information describing the water environment should be linked with time series information about water measurements to form a complete information system for water resources.

7.2 Digital Elevation Models (DEMs)

Digital Elevation Models (DEMs), also called Digital Terrain Models (DTMs), are used in water resources management and planning for hydrological applications to simulate overland flow routing and provide a three dimensional topography model. DEMs are used to delineate watersheds, analyze channel networks, predict soil water content, predict erosion potential, model non-point pollution and carry out flood and hydrograph analysis (Duke, Kienzle, Johnson and Byrne, 2003).

The most common DEM data structure is the raster or grid structure. This normally consists of a matrix of square grid cells with the mean cell elevation stored in a two-dimensional array. Other DEM structures, such as the triangulated irregular network and contour-based structure have very limited use in water resources and are not discussed further in this study. Water resources practitioners should be aware of the basic processes involved in DEMs, especially how the water flows are simulated in the models to appreciate some of the implications of using DEMs. Because DEM cells at their best spatial resolution may be as coarse as 30 m X 30 m (e.g. the United States Geographical Survey's commonly used 7.5 minute DEMs), they often do not represent artificial linear features. As a result of the coarse nature of DEMs, flow direction matrices that are derived from DEMs alone are often inaccurate (Duke *et al.*, 2003). DEMs with a grid or raster data structure use the deterministic eight neighbour (D8) flow direction algorithm to simulate flows (Figure 7.2). Other flow determination methods are also used but the dominant flow direction determination technique is through the comparison of the elevation of each cell with its eight neighbours and allocating a single flow direction from each cell to the neighbouring cell presenting the steepest gradient.

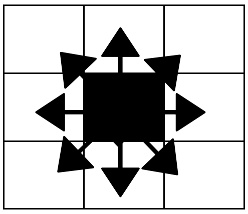


Figure 7.2 Deterministic eight neighbour (D8) flow direction in DEMs.

Each DEM cell is allocated one uniform ground level irrespective of other possible height variations within the cell. Depending on the sizes of each cell many linear features such as tillage furrows, culvert drains and road embankments are not accounted for in the DEMs. Representation of artificial or man-made linear functions on DEMs is possible through the use of specialised and separate algorithms. In the case of linear depressions, the modeller is advised to use ancillary stream data to impose or “burn” the stream vector data on to the DEM. “Burning” stream flow data involves the use of software to lower DEM cells accordingly to produce a manipulated flow direction matrix which is more accurate. However, there are terrain pits where, say, a cell-X will be lower than all the surrounding cells such that flow from this cell-X cannot be determined. Oliveria and Maidment (2000) recommended that such depressions should be filled first before imposing any vector data for linear features. They advised on a method of converting the wholly raster data into vector based polyline features to define the river reaches and other linear features as well as maintaining a raster domain for polygon features to define the sub-basins. In the case of embankments or other linear high points, a road enforcement algorithm (REA) or other software should be used to produce a secondary single flow direction matrix that accounts for roads and elevated linear features. The matrix is then imposed on the topographically derived (DEM) flow direction matrix.

The accuracy of DEMs cannot be better than the source data. The data used in DEMs, are usually derived from aerial photographic interpretation, topographic maps, field surveys, remote sensing and geographical positioning systems (GPS). In many cases there is no quantitative assessment of DEM accuracy, and error propagation to secondary parameters such as slope and aspect is not addressed (Monckton, 1994). The result is that poor decisions are made on the basis of poor input data.

To determine DEM accuracy, independent knowledge of the topography is required to determine the difference between the digital surface and the real elevations of the same locations on the ground. This requires both a suitable sample of ground truth points, and suitable statistics from which to derive error terms (Barringer and Lilburne, 1997). Modellers are cautioned against taking such ground truth points from the same topographic database as the contours, in the form of local spot heights recorded at trig stations and local peaks. Trig beacons and spot heights do not provide a good sample of the landscape since they over-represent peaks, under-represent low areas, and may be non-randomly distributed with a bias towards hilly areas. Acquisition of ground truth points should preferably be derived by independent survey, either photogrammetric, traditional field survey or by using Global Positioning Systems (GPS) (Barringer and Lilburne, 1997).

The RMSE between DEM and ground truth elevations can be used to measure DEM accuracy:

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n} d_i^2}{n}} \qquad \text{Equation 7.1}$$

where n = number of points

$d_i = Z_{ground.i} - Z_{dtm.i}$

$Z_{ground.i}$ = ground elevation recorded at point i

$Z_{dtm.i}$ = DEM elevation at point i

Alternatively Li (1988) advocates the use of the standard error (s) and mean error ($\bar{d}$) to determine DEM accuracy:

$$s = \sqrt{\frac{\sum_{i=1}^{n} (d_i - \bar{d})^2}{n}} \qquad \text{where} \qquad \bar{d} = \frac{\sum_{i=1}^{n} d_i}{n} \qquad \text{Equation 7.2}$$

Where n and d_i are as explained for equation 7.1.

RMSE is the more widely used statistic but assumes a zero mean error ($\bar{d}$), and therefore assumes no systematic bias in the DEM. This is not a justified assumption, according to Monckton (1994), who pointed out that systematic errors occur frequently. A good example of the use of RMSE is the classification of DEMs in the USA. In the United States, DEMs are available in three levels. The classification of these levels is mainly based on accuracy (Garbrecht and Martz, 2000). In level 1, a vertical RMSE of 7 metres is the targeted accuracy standard and a RMSE of 15 metres is the maximum permitted. Level 2 DEMs have identifiable systematic errors removed and the maximum permitted RMSE is one-half of the original map contour intervals. The level 3 DEMs have a maximum permitted error of one-third of the contour interval. Water resources modellers are advised to adhere to specified DEM accuracy levels and to use the recommendations provided above in cases where standards have not been specified.

In selecting DEMs, water resources or hydrological modellers should consider both quality and resolution (Garbrecht and Martz, 2000). Quality refers to the accuracy of the elevation data, while resolution refers to the precision of the data, specifically to the horizontal grid spacing and vertical elevation increase. Quality and resolution must be consistent with the scale and model of physical processes under consideration and with the study objectives.

7.3 Databases and data models in water resources modelling

Traditionally, water resources data usually consisted of time series data on point observations of water resources phenomena, including rainfall, streamflow, water quality, and climate. Integration and the use of GIS among many other recent developments in water resources management and planning have changed the concept of water resources data. Data for water resources management are now expected to cover the management of river basin erosion, water resource quality objectives, floods, water quality, sedimentation and land use. The trend in integrated water resources management is such that data, database systems, modelling tools and water system rules must now be incorporated into a single system that can be modelled and run in unison. The design of the databases used in such integrated water systems should take into consideration the following:

- **Data formats:** The data should comply with prescribed standards in terms of formats and must be in those formats that allow integrated approaches. As an example, Maidment (2001) expressed the need for geospatial data and temporal water resources data to be captured and archived in the same formats and within the same environments. He explained that, rather than just applying GIS in water resources, spatial data and temporal data can now be viewed as just similar information sources that the water resources practitioner can access and use.

- **Data accuracy:** The maintenance of data accuracy should ideally start early, that is at data collection stages. At the water resources modelling stage, the modeller should ensure that the data used are within acceptable accuracy levels and that meta-data are also entered into the database at the same time as the data. Some data are useless when information about the data (meta-data) is not available. Meta-data in water resources should ideally include:

    - Source of data (Name of the institution supplying the data and the location of the gauge used for data observations giving the name and again using the geographic coordinates).
    - Data accuracy information (use of standard flags for each data element is preferred especially in time series data. As an example, flags for rainfall and stream flow data may include the symbol “M” for missing data, “999” for a data element that was beyond measurement capacity and “P” for patched data).
    - Confidence levels associated with observed data discrepancies. As an example the USGS gives an “excellent” rating if 95 % of daily discharges are within 5 % of the true value (Donigian, 2001).
    - The dates when the data were collected and reasons for the collection process if it influenced the data
    - Details of anything that was done to the data, for example corrections to some data elements, patching of missing values, data extensions or other forms of data manipulation
    - An accurate and up-to-date directory of station characteristics and changes that occurred during the period of data recording. The introduction of a new recording

technique or the employment of new personnel to read and record data usually introduce new trends in the data.

- **Database structure:** The structure must be simple and flexible, allowing secure storage, easy user access to data elements, and generic to accommodate linkages to other related uses that may not directly relate to water resources. As an example a person working on an agriculture study may wish to utilise the data on soils in the water resources database. If the soils data components in the water resources project are not accessible such that they have to be developed again for the agriculture project, then this database is considered to be poorly structured and formatted. The use of object-oriented programming and a relational database structure for database and model interfaces was noted in this study to be the best approach in water resources management and planning database architecture. This approach accommodates the different spatial and temporal scales as well as providing a suitable platform for direct integration with different models that will access and process the data. Another approach that may be pursued in cases where models have to link to existing databases is the use of e**x**tensible **m**arkup **l**anguage (XML) to act as the link between the existing database and the models. In this case the user interacts with the XML database management system which uses XML generated data files to transfer information between the models and the database. A methodology of developing an open modelling framework using the XML approach is presented and recommended by Kokkonen, Jolma and Koivusalo (2003) for hydrological and climatic models. The advantage of using XML or other intermediate platform is that data and model components developed independent of each other by different developers can be linked. However this method lacks the full integration that is possible when object oriented programming and a relational database structure are used.

- **Level of detail, scales and resolution:** McKinney *et al.* (1999) recommended the use of object-oriented programming coupled with a relational database to allow the possibility to vary the simulation scales in one model. This allows detailed high resolution simulations (field or plot scale) as well as large scale (regional) assessments within a single water resources model.

- **Targeted uses and output formats**: Database developers should clearly consider the implications of the various database architecture selections to ensure that the final database is technically sound and appropriate to the project needs. A database must at least satisfy the core objectives behind its development, before attempting to satisfy other peripheral needs.

- **Organisational and industrial compliance:** Databases should comply to organisational requirements as well as the industrial requirements to allow other external users to be able to access the data and also to ensure that the database can be updated from external sources. The provisions in the NWA (Republic of South Africa, 1998) on the development of national information systems should guide water resources database developments to ensure industry wide compliance.

- **Database updating methods and data entry quality management**: The methods used to update the database are crucial in database design. As an example, databases that are updated by inputs from different users in different locations will require additional and more stringent data quality management systems than those that use a single automatic entry such as a cellphone connection relaying data from an automatic water level gauge in a dam. The different requirements in database updating affect the nature of the database to be used, including: software, data structure and data storage and interfacing hardware.

- **Background of original data collection:** Data are usually collected for a specific use in a particular project such as a water resources model with unique data needs. As an example, stations for measuring hydrological and climatic variables have been established for once-off projects such as dam developments and closed soon after the project is finished. The archiving of these data should be accompanied by an explanation indicating that the data were collected for a once-off project and that no further data can be obtained from that station. Another example is that of the water quality database developed for use in the model WQ2000 (Herold, 2003) for the Vaal River. Salinity was the focus of water quality assessments in the WQ2000 study while other water quality variables received insignificant attention. Users of such a database may end up developing or selecting a model that is strong on salinity thus forcing their modelling exercise to focus only on salinity, which is just one of the many water quality problems in the Vaal River. Other major water quality problems such as the high levels of phenols and sulphur oxides from the electricity power stations and mining activities in the upper Vaal River catchment area will need to be accounted for to ensure completeness in the water resources modelling process.

7.4 Stakeholder factors in water resources modelling

In the past decade, water resources management has faced a paradigm shift, from a top-down approach to participatory management (Flügel and Staudenrausch, 1999). Stakeholder participation now plays a significant role in the development and use of water resources management tools. The range of human related issues influencing the water resources tools include: experiences and preferences by developers, owners of the problems and stakeholders, as well as knowledge and abilities of developers and users. The model conceiver's perceptions, which are influenced by his/her value system, are also crucial as they are the basis for most of the choices made during model development. Kloprogge and van der Sluijs (2002) pointed out that a model and its outcomes may be difficult for users and stakeholders to accept which will lead to conflict if the model does not adequately reflect their knowledge and perspectives.

The process of solution development in water resources management, including the development of models, should take into account the following stakeholder factors:

- Information made available for decision making must be supported by adequate knowledge, data and a good appreciation of the problem. Poch (2002) recommended that environmental models should not only seek to process numerical aspects but should include reliable knowledge and experiences from experts and the wider public participants.
- Project proponents should ensure that they are prepared to negotiate with stakeholders and provide alternatives and offer compromises. A case study involving poor consultation is presented in the Orange River Basin Development study by the Secretariat of the World Commission on Dams. This study revealed that the little consultation that took place before the implementation of the Orange River

Development Project (ORDP), and provided no alternatives to stakeholders. Stakeholders in the Orange River Basin are still disgruntled by the fact that they were given no alternatives during the consultations (WCD, 1998).

- Suitable human expertise with skills in all the important disciplines are important in water resources model development. Winiwarter and Schmak (2002) advised that models that simulate natural systems such as water resources models need to be assembled by at least two types of experts: those that understand the natural system, and those that are able to transform the concepts into computing algorithms.
- Methods should not be developed simply to please influential groups of stakeholders, but rather the groups should be empowered to understand all the variables involved so that they can contribute competently to the development of the best methods.
- For models to be used effectively, stakeholders should understand model assumptions, content, capabilities and output. They also need to have confidence in the model validity and view it as a useful decision support tool that is transparent, flexible and accessible (Palmer and Woods, 1999).
- Stakeholders should be involved early in the solution development process to accommodate their participation in the solution development and hence provide a basis for long-term ownership of solutions. In South Africa, platforms for stakeholder involvement include workshops, conference sessions, questionnaires, user forums and targeted publications. The allocation of resources to involve stakeholders should be carefully planned and managed as it can delay or derail a project if poorly planned and implemented. Modellers should avoid over commitment of resources to stakeholder involvement. It has been observed and documented that stakeholder involvement cannot result in a perfect decision. d'Aquino (2002) advised that a perfect decision can never be found in catchment modelling which aims to fulfil all stakeholder perceptions. Giraud *et al.* (2002) recommended the use of socio-economic behavioural models by stakeholders as platforms for group contributions to the design of solutions in catchment based water resources management. Giraud *et al.* (2002) also argued that the stakeholders have a strong influence on catchment based water management but usually lack the tools to make well-informed and well-structured group contributions.
- Long-term commitment by problem owners, project funders and other involved stakeholders is crucial for the sustainability of water resources solutions.

- Authorities or those responsible for financing solutions in water resources tend to target the reduction of costs in project implementation by using all possible actions including limiting stakeholder involvement and even scaling down the Environmental Impact Assessments. The WCD (1998) pointed out that the South African parliament quickly authorised the implementation of the first phase of the ORDP after inadequate consultation of stakeholder and environmental impact study to reduce costs and avoid possible delays. However, water resources practitioners should note that the acceptance and ownership of water resources solutions by stakeholders is in fact one key parameter used to measure the success of water resources management and planning. In evaluating the risks associated with IWRM projects and stakeholder needs, Rees (2002) also pointed out that one of the key objectives in integrated water resources management is the maximisation of total social welfare.

7.5 Summary of recommendations on spatial data and stakeholder inputs

All water resources management problems inherently have a spatial dimension. The development of models for water resources management tools should always seek to include a GIS approach for handling spatial data. The use of GIS should not be limited to mapping but should ideally involve the following:

- Data analysis and model output predictions
- Storage of data
- Model interfacing
- Post processing
- Results presentation
- Model documentation support
- Data and study area displays

Model user and developers should note that the type of GIS coupling used in water resources management tools will affect the kind of use that will be possible, as well as data management. In this study, the model developers and users are encouraged to develop full integration of models and the GIS tools, where spatial data are available and are required in the modelling process. This allows a single database to be developed for spatial data and other types of input data. Seamless integration of GIS and water resources models has the added advantage of reducing sequential batch processing of model modules, thus eliminating the potential for input errors, and allowing multiple module simulations at each time step.

In cases where GIS software costs restrict its use, modellers and developers in water resources projects should ideally seek suitable open source GIS software and utilise it at no added costs in their projects. Listings, information and download linkages of hundreds of such free open source GIS software are available on the world wide web. Ramsey (2004) also provides technical assessments of several GIS tools that can be utilised in various GIS projects.

When selecting an Open Source GIS or Freeware GIS tool, the user or model developer should consider a number of factors. Some of the most important issues for consideration deal with the specifications of the tool. These include:

- What the GIS software can be used for.
- The implementation language used in the tool.
- The users or developer operating system requirements.
- The spatial data input file sizes and formats.
- Specifications of the computer requirements for running the GIS tool.
- Availability, format and adequacy of GIS user or developer support.

Digital Elevation Models (DEMs)

Ideally, DEMs should be used in models where the water resources planning and management questions to be addressed involve variables that are dependent on land elevation. Modelling variables for which DEMs will be required include: water flows, orographic rainfall, air current flows, groundwater levels and river recharge.

In selecting a suitable DEM, water resources or hydrological modellers should consider both quality and resolution, where quality refers to the accuracy of the elevation data, while resolution refers to the precision of the data. Since the accuracy of DEMs cannot be better than the source maps, photos and other documents, the selection of GIS data sources should receive special attention.

Databases

In the development of water resources databases, modellers should aim to develop a single database for all input data as well as input parameters. Ideally, a single database that can be applied in a number of related models is required. The NWA already promotes the development of such national databases.

Another important aspect of good data management is to provide meta-data for all the model input data.

Stakeholders

The development of solutions that are appropriate and acceptable to all stakeholders is also discussed in this chapter as an important characteristic of good water resources management and planning. In most cases, stakeholders have different levels of understanding and appreciation of the issues surrounding the water resource modelling processes. Water resources projects should therefore include initiatives to improve the levels of stakeholder understanding, thus empowering the different stakeholders to ensure that they share a common understanding and are able to provide meaningful support and feedback in water resources solution developments.

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.

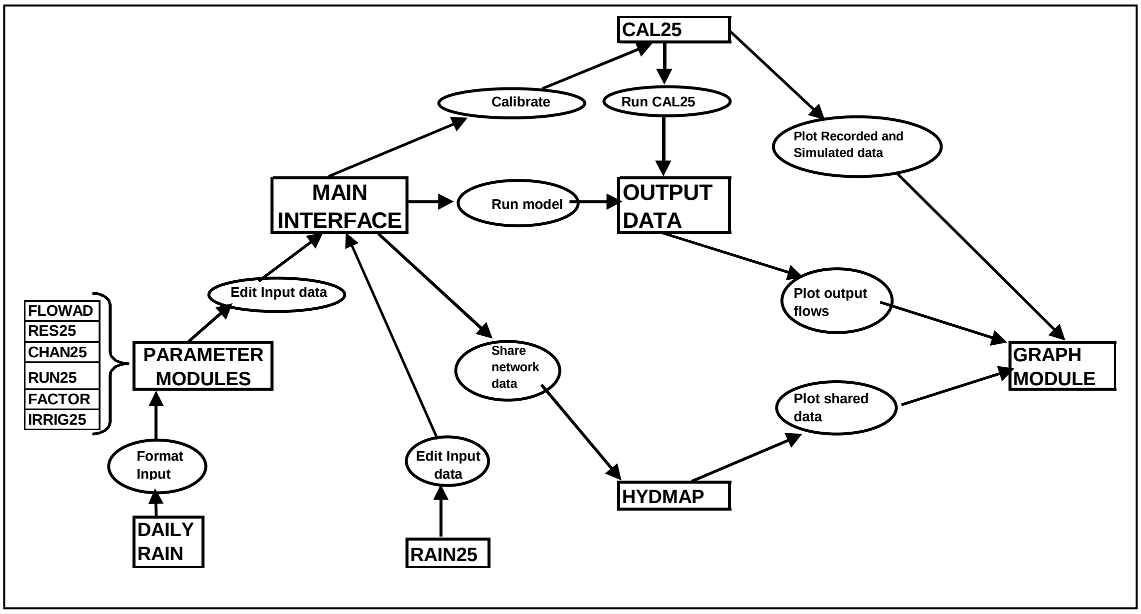


Figure 8.1 **HYDRO25 flow diagram showing the main modules linkages.**

• 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.

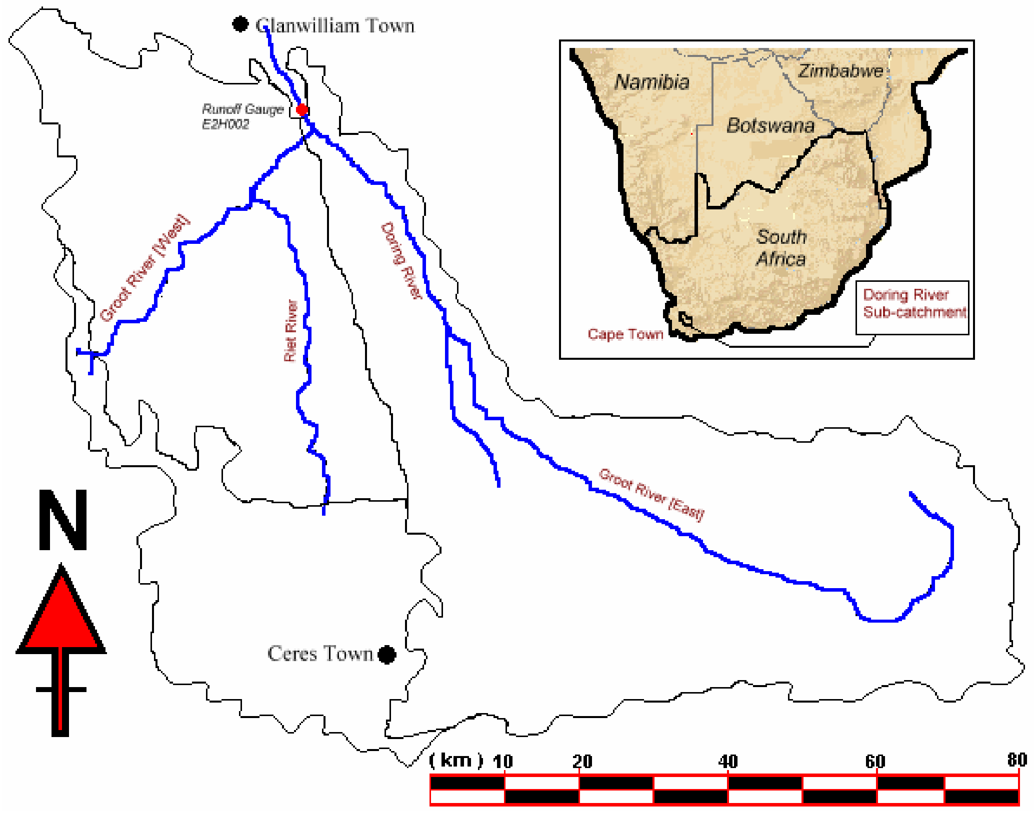


Figure 9.1 **The study area (Insert map shows location in Southern Africa).**

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

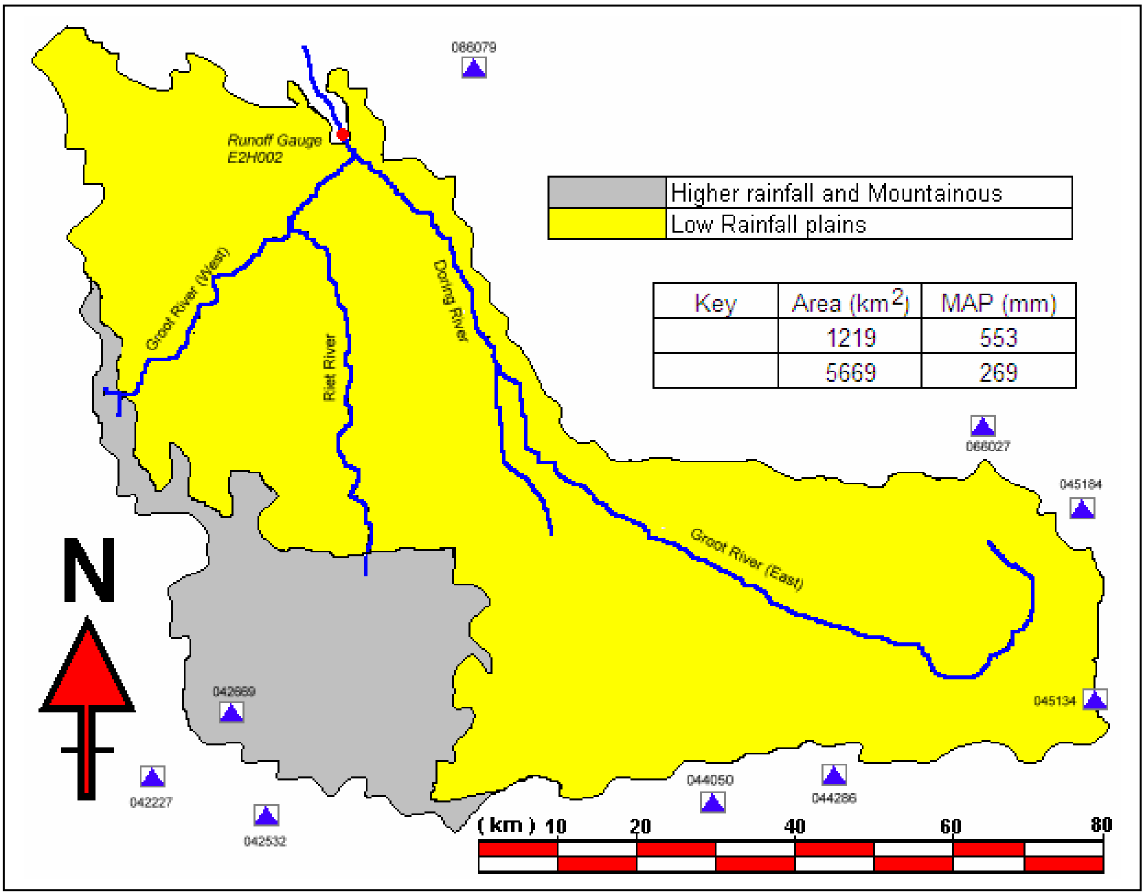


Figure 9.2 Doring River system catchment divisions based on mean annual rainfall distribution, and showing positions of rainfall gauging stations used in this study.

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.

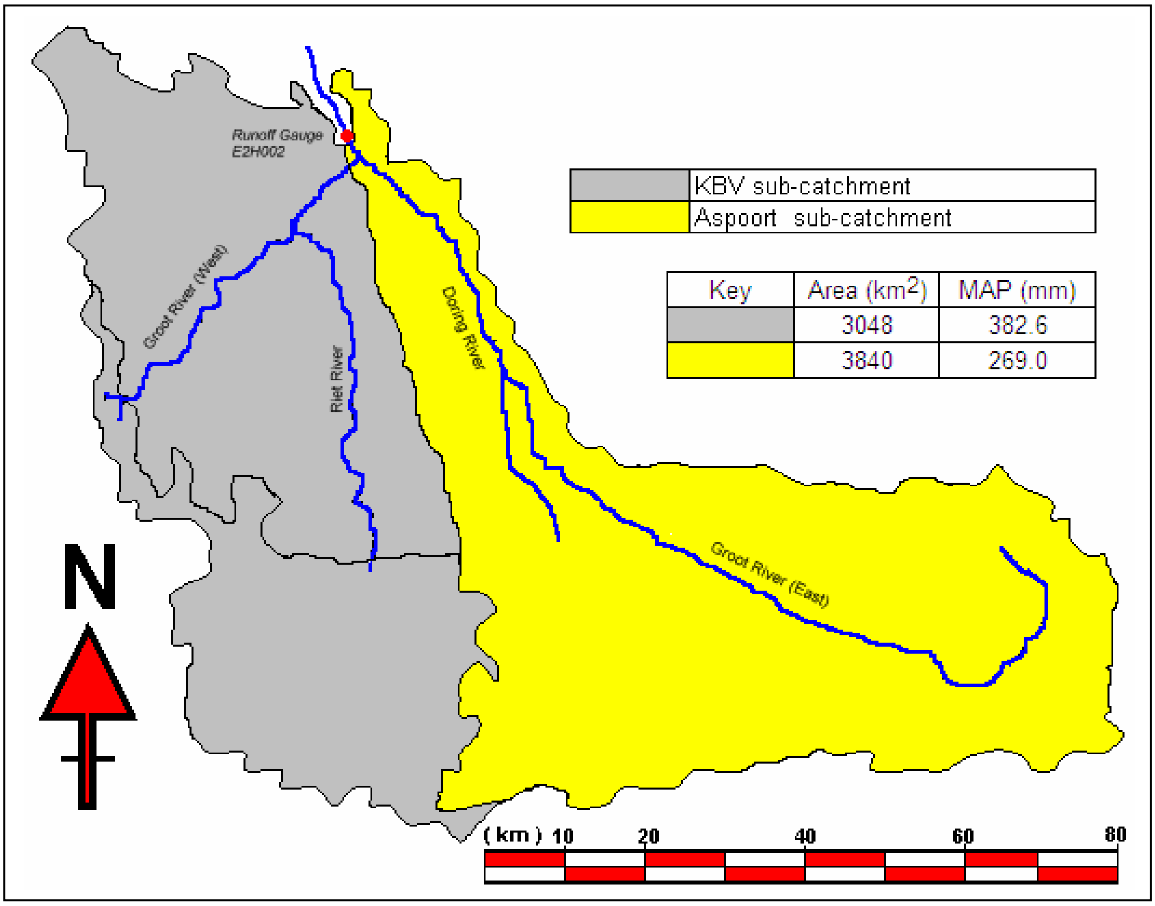


Figure 9.3 **The KBV and Aspoort sub-catchments used in simulating historical and proposed developments.**

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.

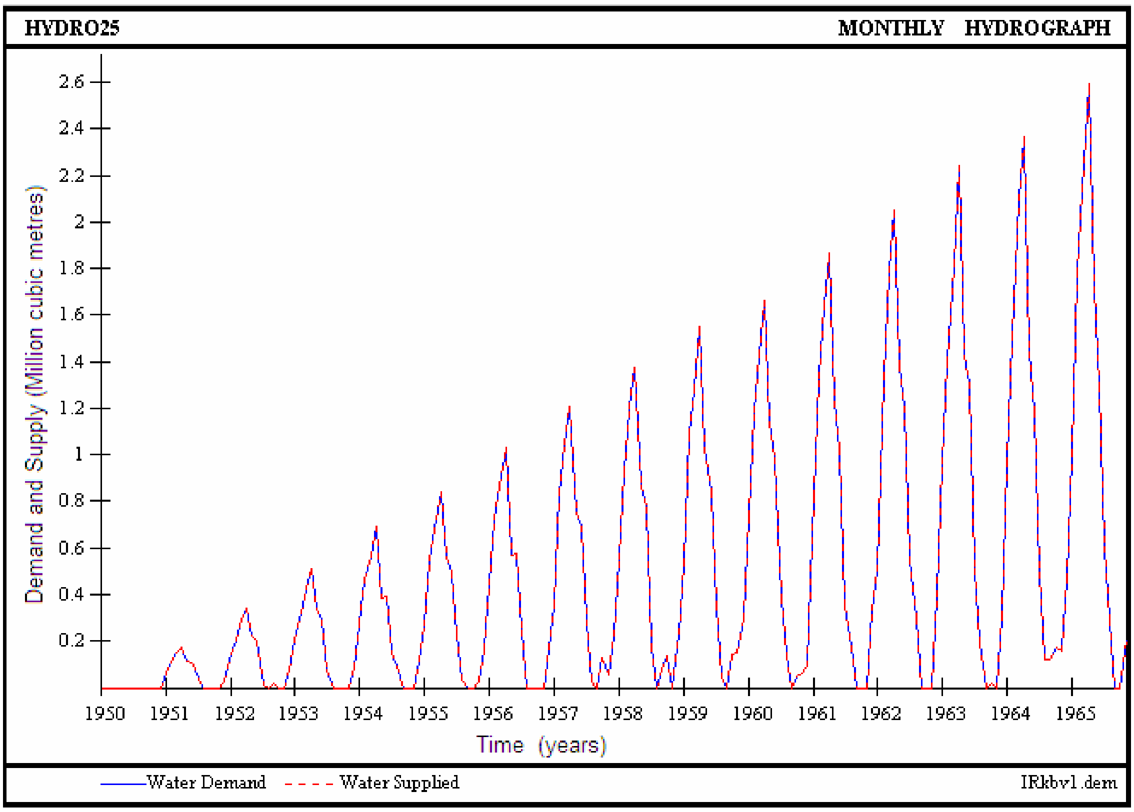


Figure 9.4 **An example of a graphical plot used in visual evaluations of model performance.**

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.

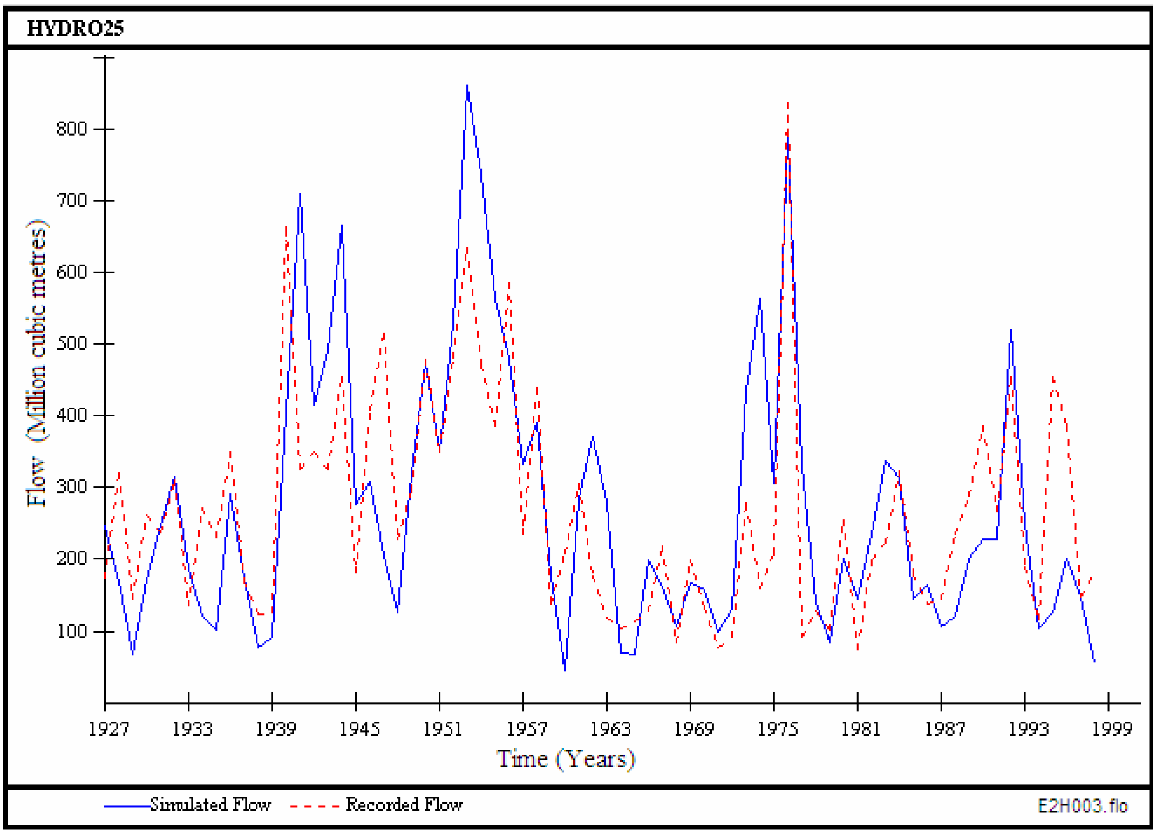


Figure 9.5 Simulated and recorded monthly flows in the Doring River at gauge E2H003.

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.

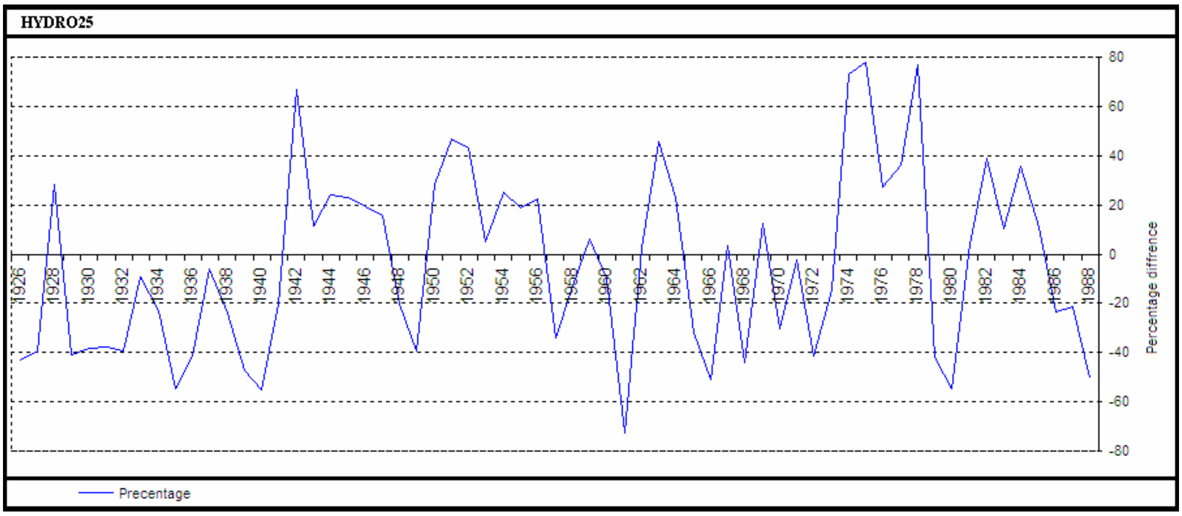


Figure 9.6 **Percentage difference between simulated annual flows and recorded flows at gauge E2H002.**

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.

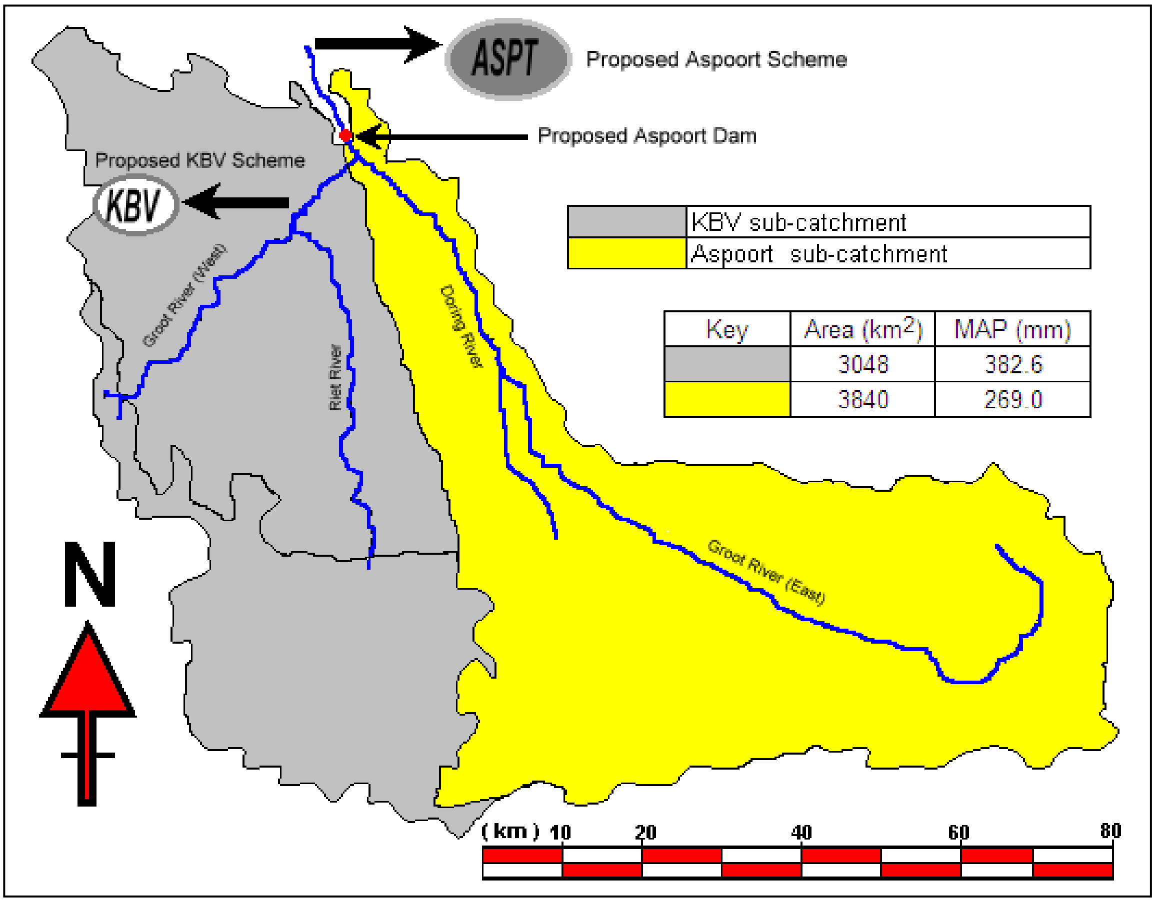


Figure 10.1 Location of upper Doring River system and approximate locations of the associated irrigation development proposals.

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.

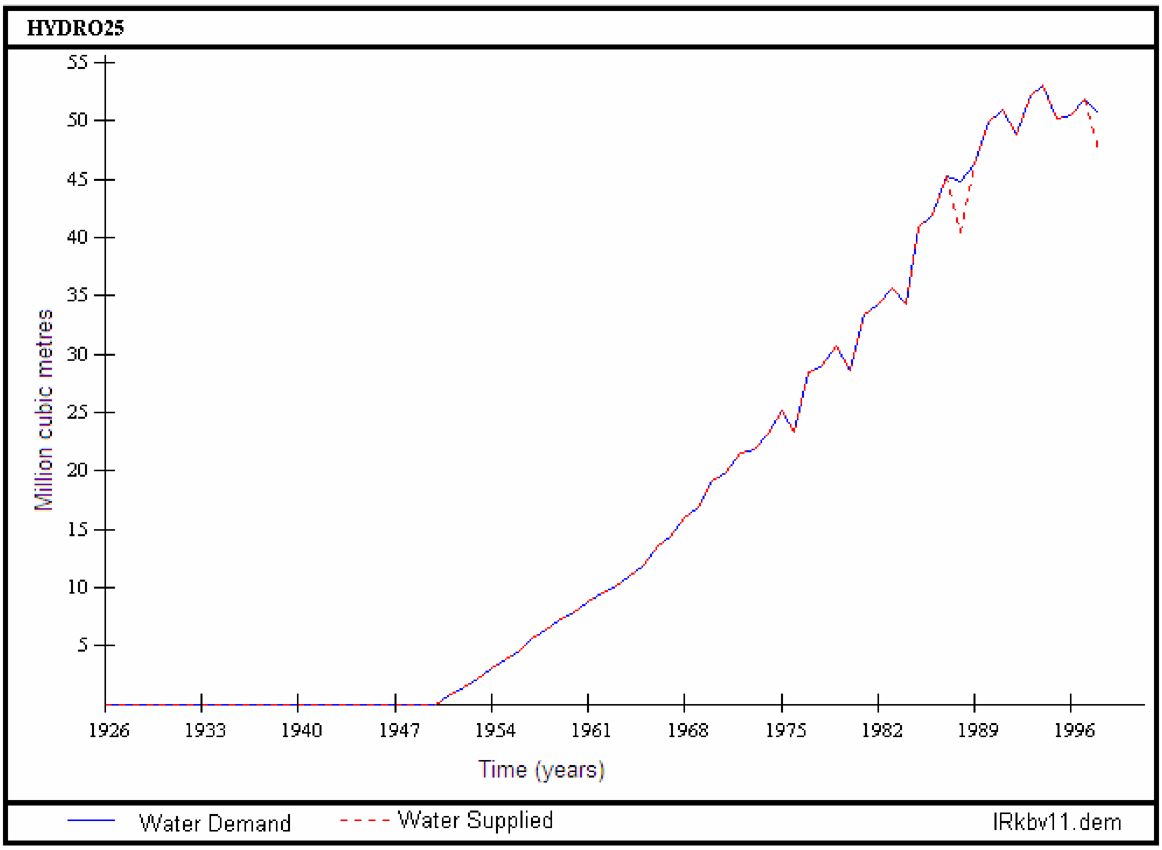


Figure 10.2 Results of simulation of progressive increase in irrigation water demand and quantity of irrigation water supplied between 1926 and 1999.

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.

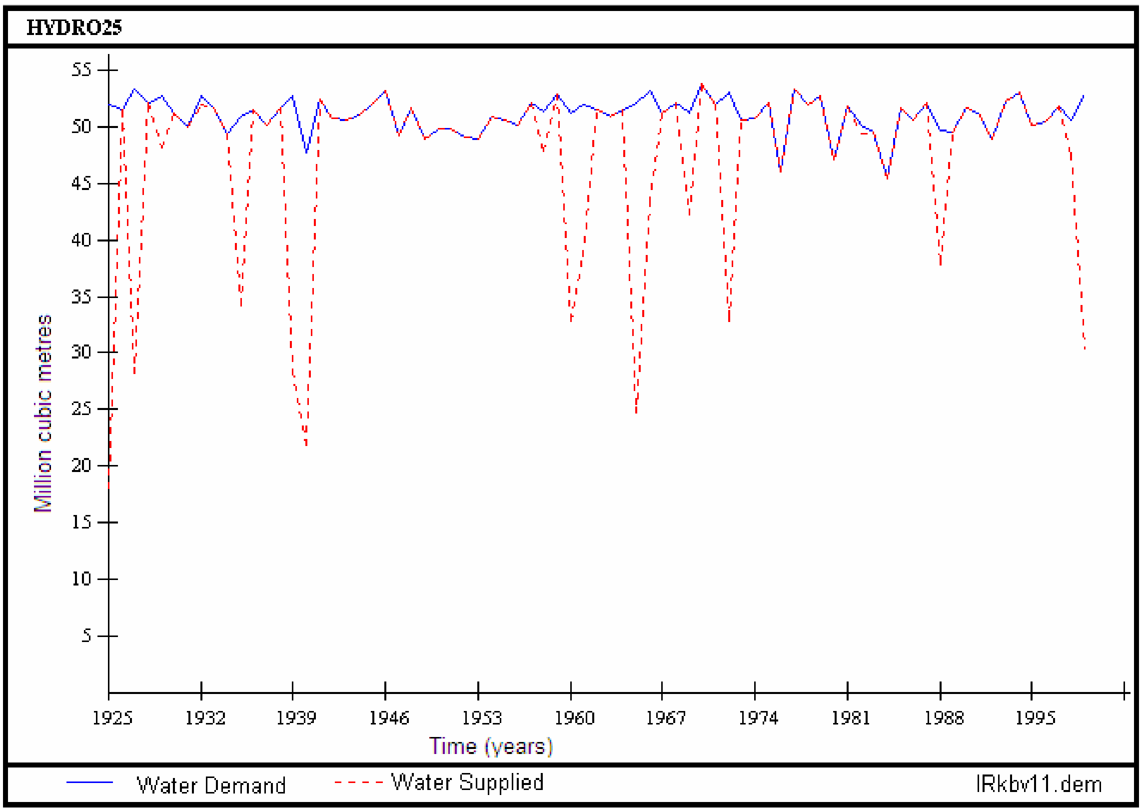


Figure 10.3 Irrigation water demand and supply for the KBV scheme with catchment development in 1999 maintained over the entire record length (1925-1999).

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.

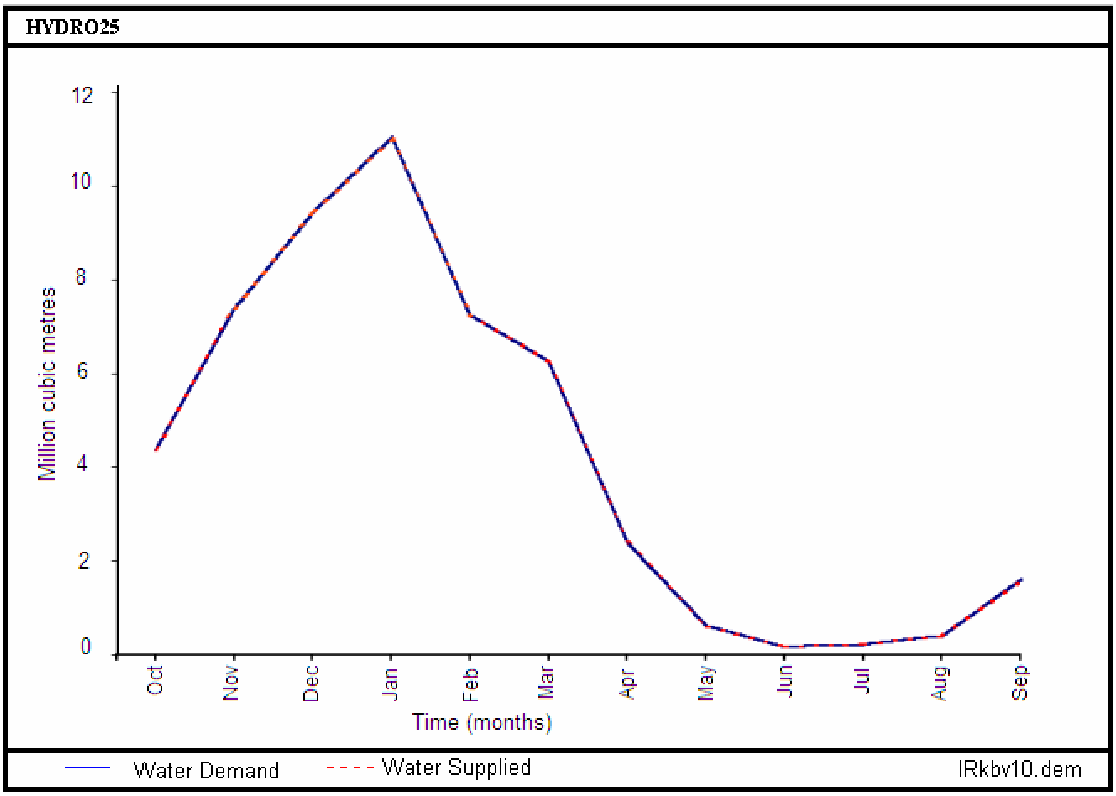


Figure 10.4 Typical monthly distribution of the water demand and supply in the KBV area.

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.

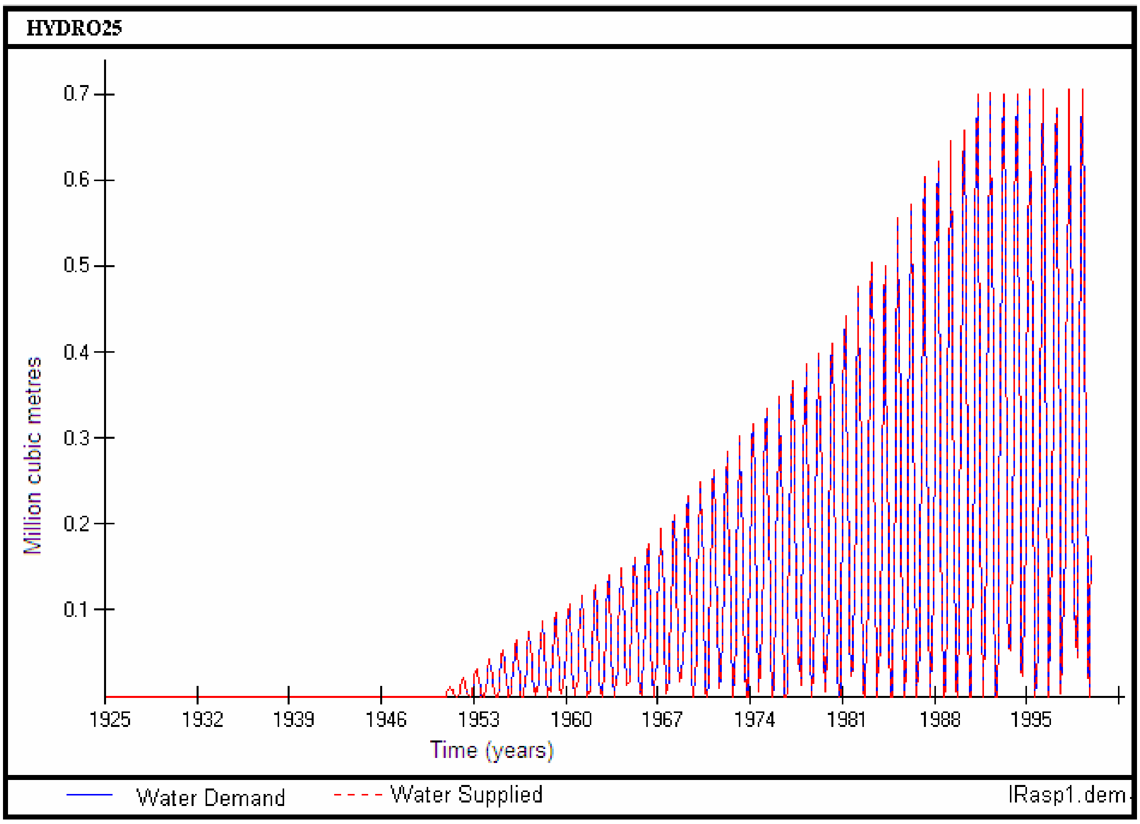


Figure 10.5 Growth in irrigation water demand and supply for monthly time steps in the Aspoort scheme, based on catchment development over the period 1925 to 1999.

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).

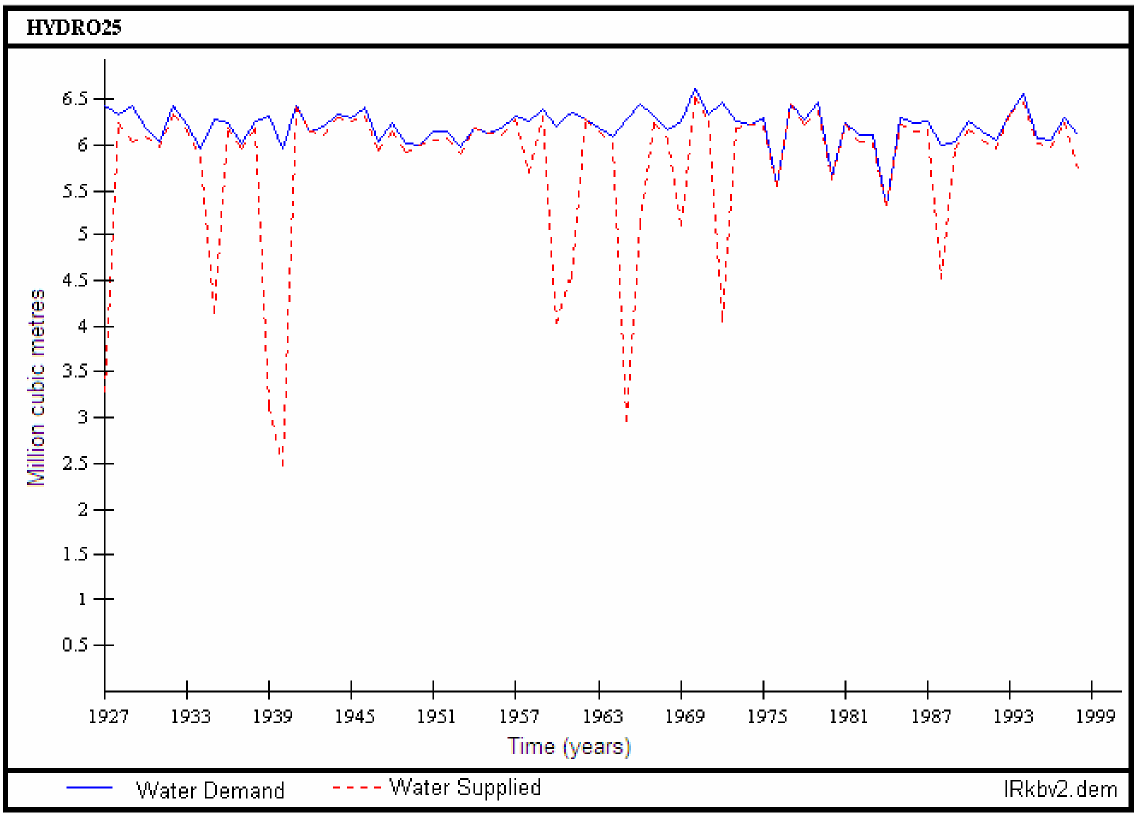


Figure 10.6 **Annual irrigation water demand and supply results for the proposed 700 ha irrigation in KBV.**

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.

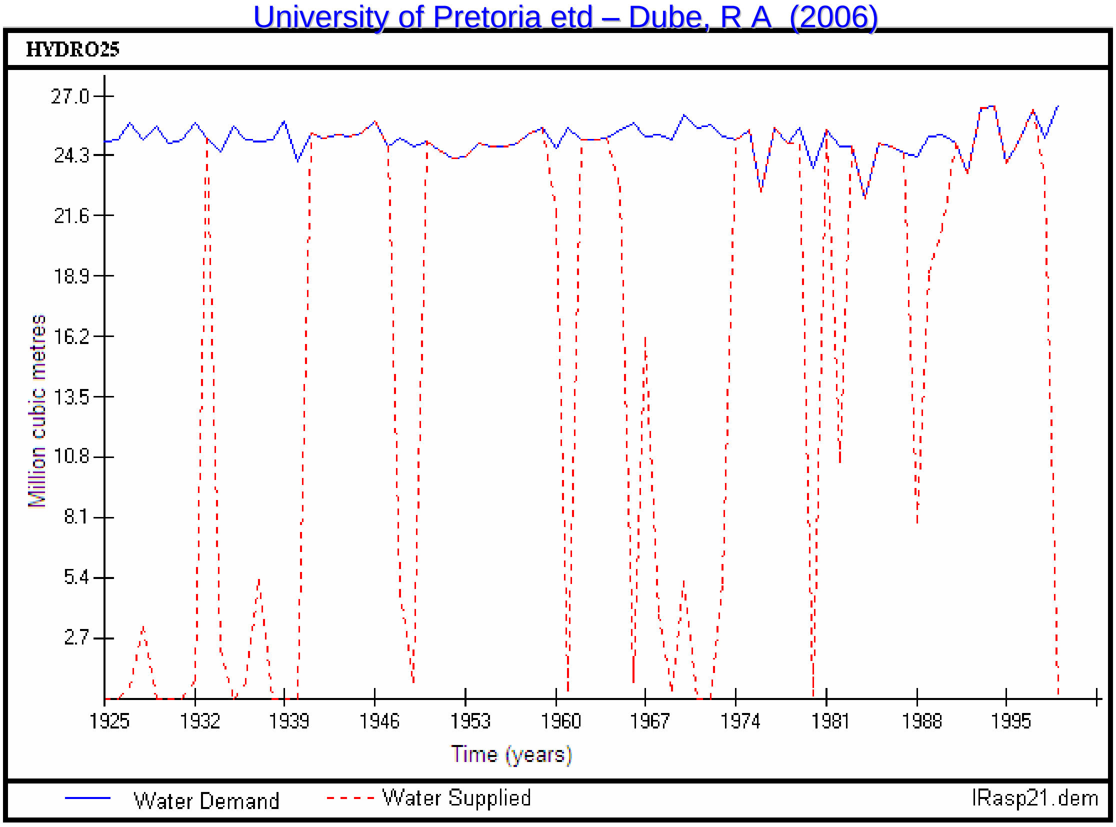


Figure 10.7 Irrigation water demand and supply for the proposed 3000 ha development option at Aspoort.

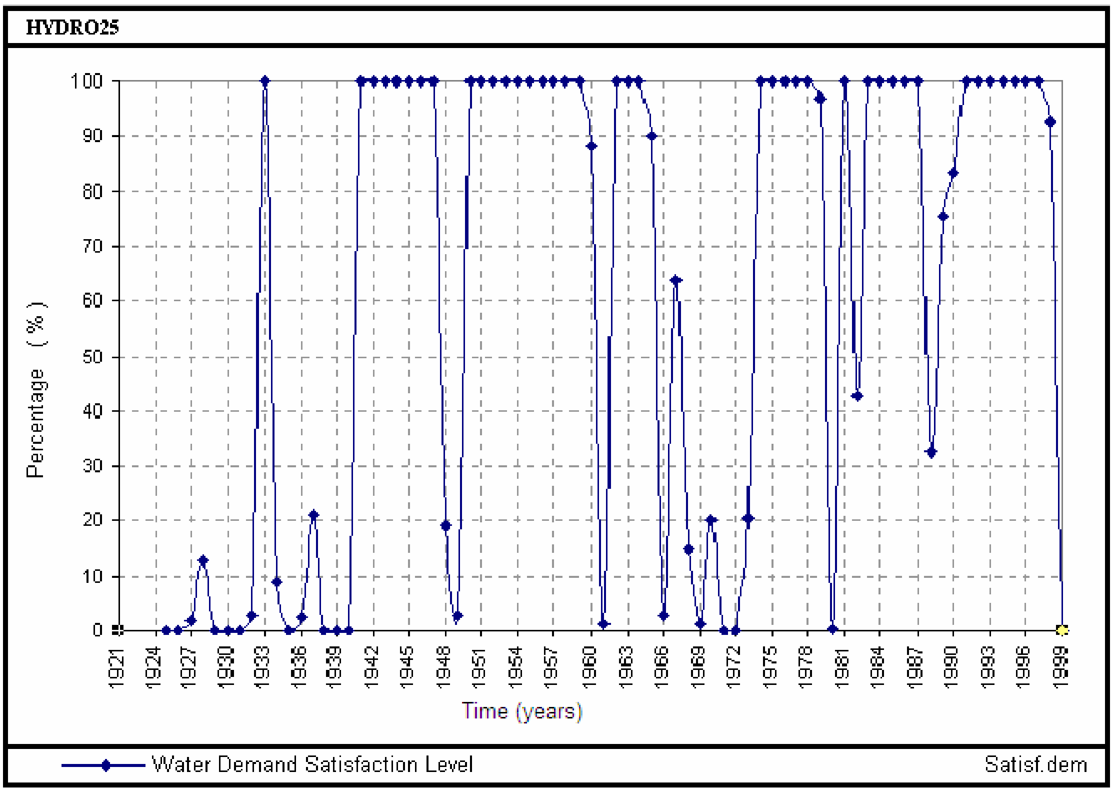


Figure 10.8 Irrigation water supply as a percentage of annual water demand for the 3000 ha development option at Aspoort.

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.

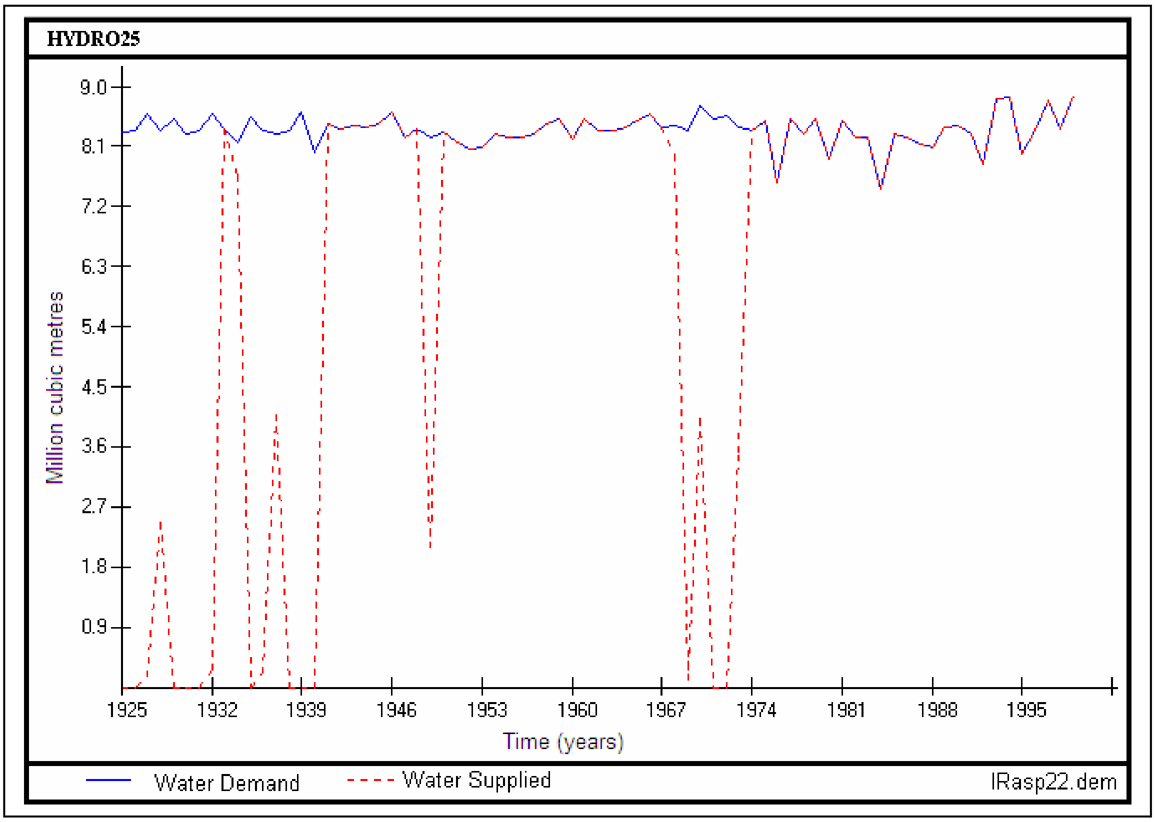


Figure 10.9 Irrigation water demand and supply for the proposed 1000 ha development option at Aspoort.

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.

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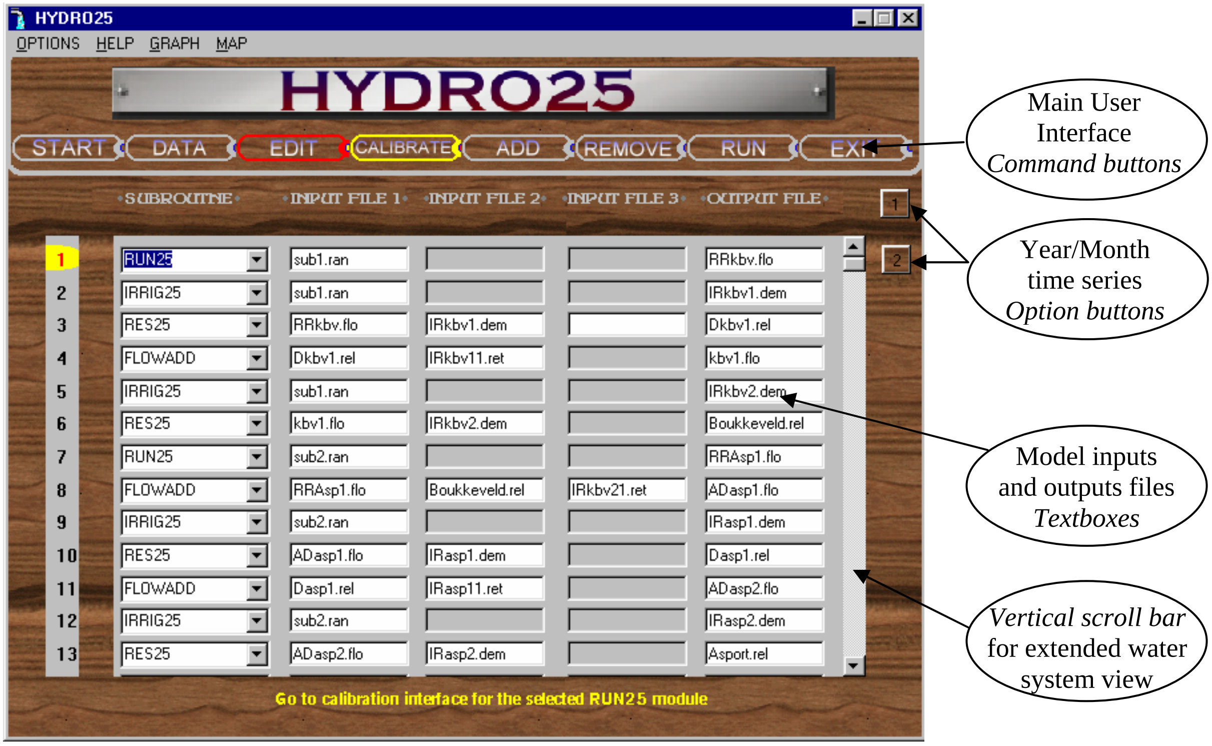
Appendix A1: HYDRO25 model development case study -HYDRO25 Model modules and interfaces

1.1 The main user interface

The main user interface, Figure A1.1 below, supports the code that runs the model and allows the user to link to all the other functions in the model. The user can access more than ten other major user interface forms through the main user interface.



	SUBROUTINE	INPUT FILE 1	INPUT FILE 2	INPUT FILE 3	OUTPUT FILE
1	RUN25	sub1.ran			RRkbv.flo
2	IRRIG25	sub1.ran			IRkbv1.dem
3	RES25	RRkbv.flo	IRkbv1.dem		Dkbv1.rel
4	FLOWADD	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	FLOWADD	RRAsp1.flo	Boukkeveld.rel	IRkbv21.ret	ADasp1.flo
9	IRRIG25	sub2.ran			IRasp1.dem
10	RES25	ADasp1.flo	IRasp1.dem		Dasp1.rel
11	FLOWADD	Dasp1.rel	IRasp11.ret		ADasp2.flo
12	IRRIG25	sub2.ran			IRasp2.dem
13	RES25	ADasp2.flo	IRasp2.dem		Asport.rel

Go to calibration interface for the selected RUN25 module

Main User Interface *Command buttons*

Year/Month time series *Option buttons*

Model inputs and outputs files *Textboxes*

Vertical scroll bar for extended water system view

Figure A1.1 The main user interface of the HYDRO25 model.

In the main user interface a water resources network can be loaded by opening an existing network file or by creating a new file. The water resources network is created or edited from the main user interface by accessing and editing inputs via interfacing with input forms, calibrating the model and creating suitably formatted daily and monthly rainfall data. The development of a water resources network involves adding or removing modules, selecting and editing the inputs to the different modules, generating suitable rainfall inputs and calibrating the model against recorded data. The main user interface does not support saving of changes to the input file data or any other editing; this is done in the other user interface forms while the main user interface's primary functions are to provide access to other modules, to show modules and file linkages and to run the model. The run procedure in the main user interface runs a network file developed through the use of the other module interfaces.

1.1.2 The main user interface controls

The main user interface has controls that fall under the following broad groups or types:

(1) Menu buttons
(2) Command buttons
(3) Option buttons
(4) Text boxes
(5) Other controls

A number of controls falling under "other controls" are not directly useful to the user's interfacing and will not be dealt with in this discussion. These controls work behind the visible interface and include controls to place timing procedures, to keep the user events in temporary memory and to determine what the user wishes to do. The controls that are important in interacting with the model in the main user interface are as follows:

(1) Menu Buttons

Options: The "OPTION" menu button gives access to the following sub-menus:

"**Edit routines** "

This sub-menu enables editing of the modules and model calibration. On clicking the Combo boxes, a disabled state is changed to an enabled state, so that the user can select from the listed module names and edit the inputs for the module.

"Run mode "

This sets the model into a running mode such that the user can run the model. The Run mode status is lost on accessing other routines that can be used to change the contents of a network file, so as to avoid running an incomplete network file or a network that is in the process of being edited.

"Cut routine"

The button allows the user to put the "Remove" button into the cutting Status, a state where modules can be completely removed from the network. On clicking the "Cut routine" menu button, a sub-routine number that is highlighted in red with a yellow surrounding, is changed to show a blue surrounding. The blue surround shows that this sub-routine will be completely removed from the network when the "Remove" button is clicked. The network file will be resaved without the sub-routine with the blue background colour when the "Remove" button is clicked. The modified network will then be displayed in the main interface view. This is the only situation where an existing network file can be opened and resaved in the main user interface. In all other cases the network file is saved in the other module parameter interfaces. A short description of the "Remove" button's functions and attributes is displayed when the computer pointer is moved on the "Remove" button. The message displayed will change accordingly when the button's function changes.

"Graph"

The "Graph" button works in conjunction with the two option buttons captioned 1 and 2. The "Graph" button is used to display a graphical representation of an existing file whose name is displayed on the main user interface. The graph can be for annual values if option 1 is selected or a monthly presentation if option 2 is selected. To use the graph button the user should select the option of annual or monthly graph, and then click in the name of the file to be displayed, then click the graph menu button. Clicking the "Graph" button after clicking the input file 2 text box of a RES25 module will display plots representing both water supplied and the water demanded if the model has been run.

"Exit "

The "Exit" menu button will end the application and unload all forms associated with the model.

(2) Command buttons:

The command buttons are highlighted with a yellow border on receiving focus, that is when the computer pointer is moved on them, without clicking. A short description of what the button can do when clicked at the moment that they receive focus is displayed at the bottom of the main user interface. On a successful click event the button border is changed to red. The highlighting of the border with different colours gives a user an idea of the processes that he/she will be going through. A button that does not change its border colour on receiving focus or clicking is disabled. Clicking the corresponding menu buttons, discussed under the section on menu controls, changes the button's disabled conditions, in the case of the "Edit" and the "Run" command buttons.

"START": Clicking the "Start" button will load an existing network file for a saved water resources network or an empty network file that already exists. A new network file can also be saved after clicking the "Start" button. The user is given a choice of creating a new file or using an existing network file when he/she clicks the "START" button. The data in the network file are displayed in the main user interface view window when a network file is opened. Editing or calibration is possible only on an active network file whose modules are displayed on the main user interface, while running of a network file does not require that the network be displayed.

"DATA": The "DATA" button allows access to the user interface that facilitates the generation of monthly and daily rainfall inputs. On clicking the "DATA" button a set of choices are made available to the user. Selecting the first option will immediately display the RAIN25 module interface. In this module several monthly rainfall files from a specific catchment being modelled can be used to generate a single file with rainfall expressed in percentages of the catchment's overall MAP. Selecting a second option will display the Daily-Rain module interface. This module can be used to generate long-term daily rainfall data. These data are generated from existing records that are in the ACRU single format (Dent, Smithers, Lynch and Schulze, 1995). The single format consists of daily rainfall data in two columns consisting of the date on the left and the rainfall in millimetres separated from the corresponding dates by at least one space. The ACRU single format was chosen here because it is in this format that the author was able to secure most of the daily records in processed form for South African catchments. The ACRU data format can be obtained from the SBEEH at the University of KwaZulu-Natal. The long-term daily rainfall data are useful for estimations of daily water balances in the model from which the monthly model is built. The model does not lump all the rainfall at the end or beginning of a month but identifies the existence of smaller time steps up to a duration of one day. In the absence of the daily rainfall data file a default rainfall distribution pattern is used. The rainfall distribution pattern used in the model's default pattern is discussed in Section 1.2.3 of this Appendix.

"EDIT": The "EDIT" button is disabled on starting an application and when a new network file is opened. The button is enabled when the menu button captioned "EDIT" routines, is clicked. The “EDIT” button gives access to the parameter input module interfaces. A parameter input module can be accessed using the "EDIT" button if the module has been selected and a highlighted module number is showing to its left. To specify the module to edit, the user should click in the box displaying the module name. Pressing the "Enter" key while a module number is highlighted will perform the same function as clicking the "EDIT" button.

"CALIBRATE": The "CALIBRATE" button works with the RUN25 module. This button displays the CAL25 calibration module interface when it is clicked while a RUN25 module has a highlighted number to its left. The calibration will only apply to the RUN25 sub-routine that was highlighted when the "CALIBRATE" button was clicked. Calibration in the HYDRO25 model is important for the rainfall/runoff simulation that takes place in the RUN25 module.

"ADD": The "ADD" button adds a set of dynamic controls at the end of the displayed network. The set of dynamic controls is used to develop the network by entering the sub-routine name and the names of the input and output files. On clicking the "ADD" button, four text boxes, a number label and a single combo box are added. Note that the inputs in the controls that are added when the "ADD" button is clicked are not saved, and will be lost on reopening of the network file. To save the inputs in the controls, the user should go through the editing procedure and save the appropriate renamed parameter file for the module selected in the newly added control.

"REMOVE": When the "REMOVE" button is clicked, two possible sets of events can occur, depending on whether the "Cut routine" menu button is clicked or not. Information on the event that will take place is displayed at the bottom of the form when the mouse is placed on the "REMOVE" button. The colour surrounding the sub-routine that is currently specified for editing can be used to determine what type of action will take place when the "REMOVE" button is clicked. If the "Cut routine" menu button is clicked the colour surrounding the routine number will be blue, in this state clicking the "REMOVE" button will completely remove the highlighted sub-routine, resave the opened network file without this sub-routine and redisplay the network file. If the "Cut routine" menu button has not been clicked, the colour surrounding the highlighted routine number will be yellow. If the "REMOVE" button is clicked in this situation the last sub-routine in the network is removed from the view irrespective of the position of the highlighting. This is not a permanent removal, as it is not accompanied by saving a new file. Clicking the "START" button and opening the current network file again can re-access the original unmodified system.

"RUN": The "RUN" button is usually disabled and cannot be clicked. To enable this button, the "Run mode" menu button is clicked. On clicking the enabled "RUN" button, any existing network file can be run, including the one currently displayed in the main user interface view if any. It should always be noted that the model will only run a network using files that exist in a single directory, that is the same file location path. The model will only access a single location of files in any single simulation. After a run, the user can run another network file in another directory if that network file has all the required input files in a single directory. Files that do not currently exist in a directory can be specified as inputs for other modules if modules existing earlier in the network will generate these files as outputs. If a file is not generated, or if an error occurs in an earlier sub-routine that is supposed to generate inputs for later sub-routines, then the sub-routines using the file as input will run with errors. As the simulation progresses, messages of the errors that have occurred will be shown and where they have occurred. A final message will show a summary of the errors as well as the computer location of the outputs that were generated.

"EXIT": Clicking the "EXIT" button will close the application at any time. If the button is clicked and fails to close the application, this could be due to one of the following causes:

(a) The main interface is not currently the active window.

(b) The model is currently busy, possibly running a long simulation.

(c) An error has occurred that still has to be rectified. One possible error that applies to all Windows application is that the application will have failed to respond. If it is only a single application that has failed to respond that application can be stopped by pressing Ctrl + Alt + Del once, then selecting the application that is failing to respond and clicking the button "End Task". It is not advisable to repeatedly press Ctrl + Alt + Del as this will close the Windows application without following the proper Microsoft (MS) Windows "Shut Down" dialogue.

Other Controls:

Combo Boxes: The combo box controls are used to specify the sub-routines in the water resources system network file. The Combo box controls exist in arrays, where up to 50 controls can be displayed in an array if code restrictions are not in place or if computer memory resources are not restricting. If the model being run has no code limitations on the network file length then the user should take precautionary measures when running long networks. Loading several controls on the main user interface with many other open Windows applications strains the computer memory capacity. Some memory problems in the operating system will leave no space for an application to run its error handling procedures, resulting in the computer completely failing to respond to any commands. The ultimate solution will be to restart the computer, a process that involves switching off the computer without following the recommended procedures of switching off the Windows application system.

Text boxes: Four text boxes are made available for each sub-routine. Some of the input file text boxes will not be enabled, depending on the specific sub-routine they are associated with, that is the one in the same row with the text boxes. The text boxes shown in Table A1.1 are available for each of the modules that can be displayed in the main user interface view.

Table A1.1 Input text boxes in the main user interface.

Sub-routine	Number of input file text boxes	Input file 1 (should always be specified)	Number of output files	
			Displayed	*Others
RES25	3	Monthly Inflow file	1	5
RUN25	1	Monthly rainfall file	1	2
CHAN25	1	Monthly flow file	1	1
FLOWADD	3	Monthly data file	1	-
IRRIG25	2	Monthly rainfall file	1	1
FACTORFLOW	1	Monthly data file	1	-

*Others: These are files that are useful for other none key purposes, such as total abstractions, water balance file in RES25 and CHAN25 modules, which are described in Sections 1.4 and 1.5 of this Appendix.

Only the enabled text boxes can have an input file name. At least the input file name for the first entry position captioned "Input file 1" should always be specified. In the case of the rainfall data files that are specified as input, the files must have rainfall data derived from using the module RAIN25 which runs outside the network file.

Other inputs on Main User Interface

Three input files can be specified for the RES25 module. Input file 1 should always be a rainfall file. Input files 2 and 3 are abstraction files, containing data on monthly storage abstraction volumes. The output file in RES25 is a spillage file with details of water releases when a dam is full. If there are no abstractions apart from overflows, then the Input files 2 and 3 can be omitted, that is the boxes are left blank. The other sub-routine with three input boxes is the FLOWADD sub-routine. The files in this routine can be any monthly rainfall or flow files in the HYDRO25 monthly data format.

All the files specified in the input boxes should either already exist in the working directory or should be created in the modules running earlier in the network. Entry of an input file name can be achieved through one of the following methods:

(a) Typing in the name
(b) Copying and pasting a file name specified as an output in another sub-routine
(c) Double clicking on the input box to display the "Open file" dialogue box.

The first method is not advisable, as errors in typing cannot be detected easily. Method (b) is the best method to specify output files in other sub-routines as inputs to sub-routines coming later in the network. Method (c) is the best way where existing files that have been saved already can be specified. Method (c) should always be used for existing files.

In the model, a file specified as an input file is only accessed for reading purposes, without modifications. A file specified as an output file is destroyed and recreated with new data each time the model is run.

Vertical Scroll bar: The user can scroll up and down the network using this control to see other parts of the network that may not be visible in the main user interface view window.

1.2 RUN25 module

1.2.1 RUN25 general functionality

The module generates the runoff resulting from monthly rainfall input entered as percentage of the catchment MAP. The module, RUN25 is supported by a file that defines the input data and parameters relating to the catchment, as well as the relationships between the modules.

1.2.2 Mathematical structure of the RUN25 module

The Figure A1.2 below shows the schematic structure of RUN25. The structure shows how the module tracks water movement in a water system from rainfall to runoff.

In RUN25 the different processes that take place in the generation of runoff from rainfall were handled in a similar process to the illustration in Figure A1.2. Equation A1.1 shows the water balance equation used in this sub-routine. The theory behind the water balance equation is discussed in Section 1.4.2 of this Appendix.

$$Ro = Pe - Ev - In - Eo - dGw - Se + Sq + dSt \quad \text{.................................Equation A1.1}$$

Where

Ro = runoff (mm)
Pe = precipitation (mm)
Ev = evaporation (mm)
In = interception (mm)
Eo = evapotranspiration (mm)
dGw = change of ground water storage (mm)
Se = seepage (mm)
Sq = recharge (mm)
dSt = change of surface water storage (mm)

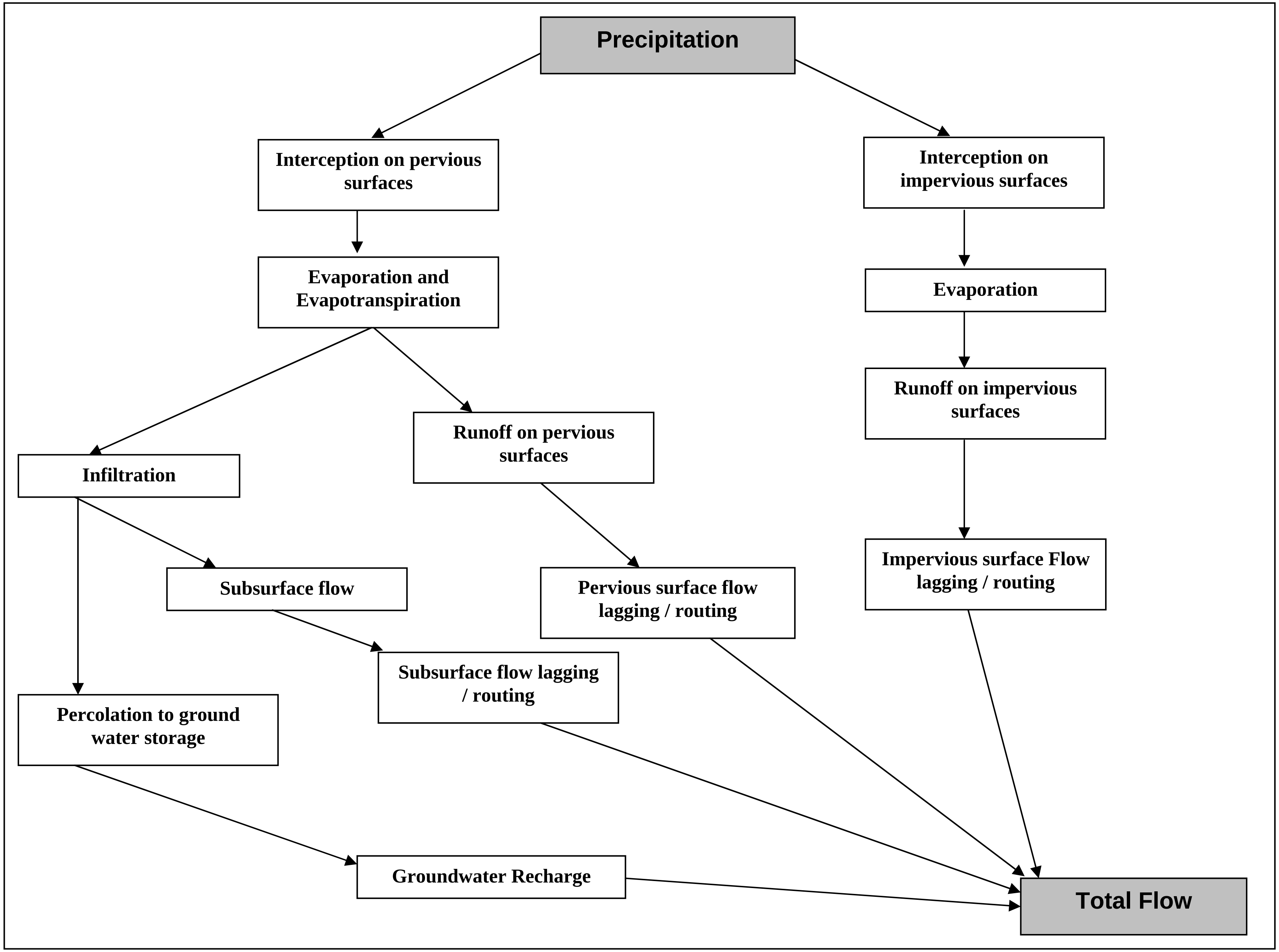


Figure A1.2 Schematic diagram of the RUN25 routine in the HYDRO25 model.

1.2.3 The water balance components in RUN25

Rainfall

The historical rainfall input data are entered in monthly time steps. The monthly figures are the percentage of the MAP that was obtained as an average of a number of records from related rain gauges in the catchment. The module RAIN25 is used to generate monthly rainfall data from a number of rain gauges that are representative of the catchment. The rainfall data, which will be in percentage units, are converted to millimetre units by multiplying percentage values with the catchment MAP. Volumetric quantities in cubic metres are obtained by multiplying the depth measurements with the total area on which the rainfall under consideration fell, usually the area of a catchment, as defined by the contour lines.

In the HYDRO25 model, monthly rainfall is not lumped as a single rainfall event but is distributed over the whole month. Two possible methods are used to spread the rainfall over the month. The method selected depends on whether daily rainfall data are entered or not. If daily rainfall data are not entered a default method based on studies by Pitman (1973) is used. This method is discussed in the following subsection.

Default rainfall distribution

Pitman (1973), made the following important conclusions on rainfall distribution where the actual pattern of rainfall is not known:

(a) The month's precipitation is equally divided into two parts where each part falls in the approximate half of the month.

(b) A small rainfall quantity associated with a single day's fall is evenly distributed above and below the line representing uniform rainfall distribution for the month.

The RUN25 sub-routine that simulates the rainfall-runoff relationship divides monthly rainfall into halves with a single peak in each half. A normal distribution is then maintained from the peaks to zero approximately midway for each month.

Long term daily rain

Daily rainfall, if included in the model system, is used to distribute the rainfall pattern on a daily basis in each month. The daily rainfall data do not have to be for the same period as the recorded monthly rainfall data being used in the simulation. The daily rainfall data are used to determine the long-term average rainfall for each day of the year up to 366 days to account for the leap years. In each month, the long-term daily rainfall values are factored such that the total from all the days makes up a single monthly unit. The daily fractions are then applied for each month to generate the amount of rainfall falling on that day of the month. This method, unlike the default method, does not apply a single distribution pattern for all months, but different distribution patterns for each month making it more accurate and flexible.

Interception

Not all rainfall reaches the land surface. Some of the rain is intercepted by foliage and other objects that stop the rain from reaching the ground. In the model intercepted rainfall is varied by adjusting the parameter "PI" which is related to monthly total interception. The Equation A1.2 shown below was used to calculate interception as derived by Pitman (1973):

$$I = x(1 - e^{yp}) \quad \text{……………………………………………………….…….Equation A1.2}$$

Where I = Total interception for the month (mm)

p = Total precipitation for the month (mm)

y, x are dimensionless constants derived in Equations A1.3 and A1.4 below:

$$x = 13.08\pi^{1.14} \quad \text{…………………………………………………………....Equation A1.3}$$

$$y = 0.0009\ \pi^{0.75} - 0.011 \quad \text{…………………………………………………….Equation A1.4}$$

Surface runoff

In the model surface runoff is considered to be derived from three components:

(a) runoff from impervious areas;

(b) “excess” runoff from pervious areas; and

(c) the contribution of ground water and subsurface flows to runoff.

Pitman (1973) performed several tests on the distribution of infiltration/absorption rates. He concluded that the best approximation of the distribution of the absorption rate could be described by a symmetrical triangle as shown in Figure A1.3.

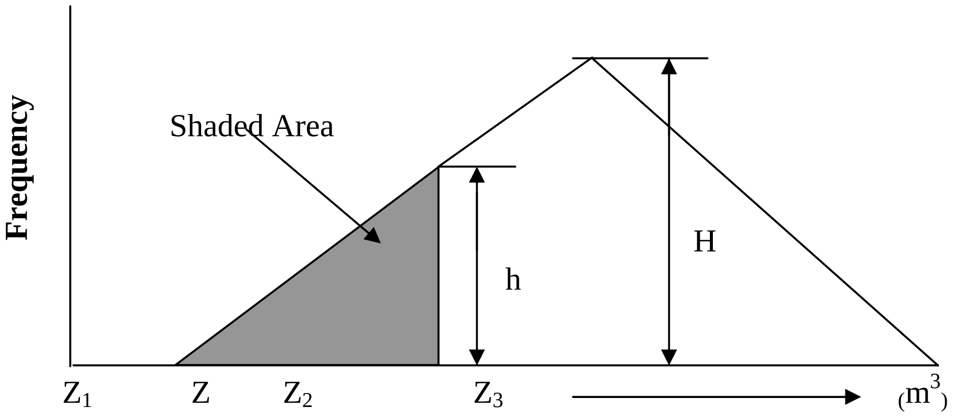


Figure A1.3 Assumed frequency distribution of catchment absorption rate.

Where:

Z = absorption rate (m^3/month)

Z_1 = minimum absorption rate (m^3/month)

Z_3 = maximum absorption rate (m^3/month)

Z_2 = mean absorption rate (m^3/month)

H = area of a section of the triangle, such as the shaded part, defines the probability of an absorption rate Z (dimensionless)

For any given rainfall input rate, r, the surface runoff, Q, is given by Equations A1.5 to A1.7 below:

For $Z_1 \leq R$ and $R \geq Z_2$, $Q = \int_{Z_1}^{r} 2(Z - Z_1)^2 / (Z_3 - Z_1)^2 .dz$ …………....Equation A1.5

R = runoff rate (m^3/month)

r = rainfall input rate (m^3/month)

Q = total runoff (m^3/month)

Therefor Q = $\frac{2(r - Z_1)^3}{3(Z_3 - Z_1)^2}$ …………………………………………………….Equation A1.6

If "r" is smaller than Z_1, there will be no surface runoff.

If "r" = Z_2 Then Q = (Z_3 - Z_1)/12 ………………………………………..Equation A1.7

For "r" values between Z_2 and Z_3, Pitman (1973) obtained a volume of runoff that could be described by Equation A1.8 below:

Q = r - Z_2 + $\frac{2(Z_3 - r)^3}{3(Z_3 - Z_1)^2}$ ……………………………………………………Equation A1.8

For "r" = Z_3 Q = 0.5 (Z_3 - Z_1) …………………………………………...…Equation A1.9

For r > $Z_{3,}$ Q = r - 0.5(Z_1 + Z_3) ………….………………………………Equation A1.10

The values for Z_1 and Z_3 which determine the surface runoff for any given rainfall input are defined as the parameters Zmin and Zmax in the model. Z_2 is the value given by $\frac{1}{2}(Z_1 + Z_3)$.

Evaporation-Soil moisture relationship

Catchment evaporation in the model is assumed to be equal to the potential evaporation, PE in millimetres, when the soil moisture, S in millimetres, is at full capacity, ST. To account for the relationship between the extremes, Pitman (1973) introduced the model parameter R. (The model parameter R is not related to the use of this letter in equations A1.5 to A1.10). The value of R, which is dimensionless, ranges from zero when evaporation ceases, to 1 when soil moisture is at full capacity. Pitman (1973) derived Equation A1.11 to determine catchment evaporation. In the equation, the parameters, PE, PEMAX in millimetres, R and the soil moisture content determine the catchment evaporation. PEMAX is the monthly pan evaporation or other evaporation figure entered for each month in the parameter file of the RUN25 module.

$$E = PE \times \left(\frac{1}{1 - R(1 - PE / PEMAX)} \times \left(1 - \frac{S}{ST}\right)\right) \text{……………………..…….Equation A1.11}$$

Runoff-Soil moisture relationship

The relationship between the soil moisture content and runoff was derived by Pitman (1973) who based the relationship on the following four parameters:

ST = Total soil moisture capacity (m^3)
FT = Runoff at soil moisture equal to ST (m^3)
SL = Soil moisture below which no runoff occurs (m^3)
POW = Power of the runoff-soil moisture curve (dimensionless)

Pitman (1973) obtained Equation A1.12 below for this relationship:

$$Q = A\,(S - SL)^{POW} \text{ ………..……………………………………Equation A1.12}$$

$$\text{Where } A = \frac{FT}{(ST - SL)^{POW}} \text{ ………..……….…………………………..….…Equation A1.13}$$

$$\text{Resulting in } Q = FT\left(\frac{S - SL}{ST - SL}\right)^{POW} \text{ ………..………………………………Equation A1.14}$$

Runoff time lag

The rainfall-runoff time lag and the attenuation of runoff as it flows from the catchment are calculated in the model using the Muskinghum equation. The Muskinghum method uses a linear algebraic relationship between the storage (S), and both the inflow (I), and the outflow (Q), together with two parameters: (K) describing lag of runoff, and (x), a weighting factor. The basic continuity or storage statement is given by Equation A1.15 below.

$$S = \frac{dS}{dt} + I - Q$$ …………………………………………………..……..Equation A1.15

The total storage is expressed as

$$dS = S_2 - S_1 = K(x(I_2-I_1) + (1 - x)(Q_2 - Q_1))$$ ……………………….....Equation A1.16

The subscripts 1 and 2 refer to the consecutive time steps in this model, a previous month with the subscript 1 and a current month with the subscript 2. A weighting factor of zero was used to account for the lagging of instantaneous runoff as used in the model.

Combining this expression with the continuity equation yields;

$$0.5(I_1 + I_2)dt - 0.5(Q_1 - Q_2)dt = S_2 - S_1$$ …………………………Equation A1.17

An algebraic modification will yield Equation A1.18 below (Raudkivi, 1979).

$$Q_2 - Q_1 = C_1(I_1 - Q_1) + C_2(I_2 - I_1)$$ ………..……………………………...Equation A1.18

Where $C_1 = \frac{dt}{K(1-x)+0.5dt}$ ………..……………………………………Equation A1.19

And $C_2 = \frac{0.5dt - Kx}{K(1-x)+0.5dt}$ ………..……………………………………....Equation A1.20

The Equation A1.18 relates to a model with the following variables:

Q = monthly runoff total at catchment outlet (m^3)
I_i = Instantaneous monthly runoff (m^3)
dt = routing period (months)
K = lag of runoff (dimensionless)
x = weighting factor (dimensionless)

S = Storage (m^3)

Two sets of runoff were lagged in the model, with runoff from the soil moisture being accounted for by using a longer lag through higher K values entered in the model as the parameter, GL. The GL values for some parts of the catchment could be as high as three months. The parameter GL should not exceed the maximum ground water contribution to runoff. Surface runoff had shorter time lags defined through the value of K in Equations A1.16 to A1.20, given by the parameter TL in the model. The value of TL can be determined by the model user through repetitive attempts. Values of TL were usually fractions of a month where low values of 0.2 months were used for some parts of the catchment.

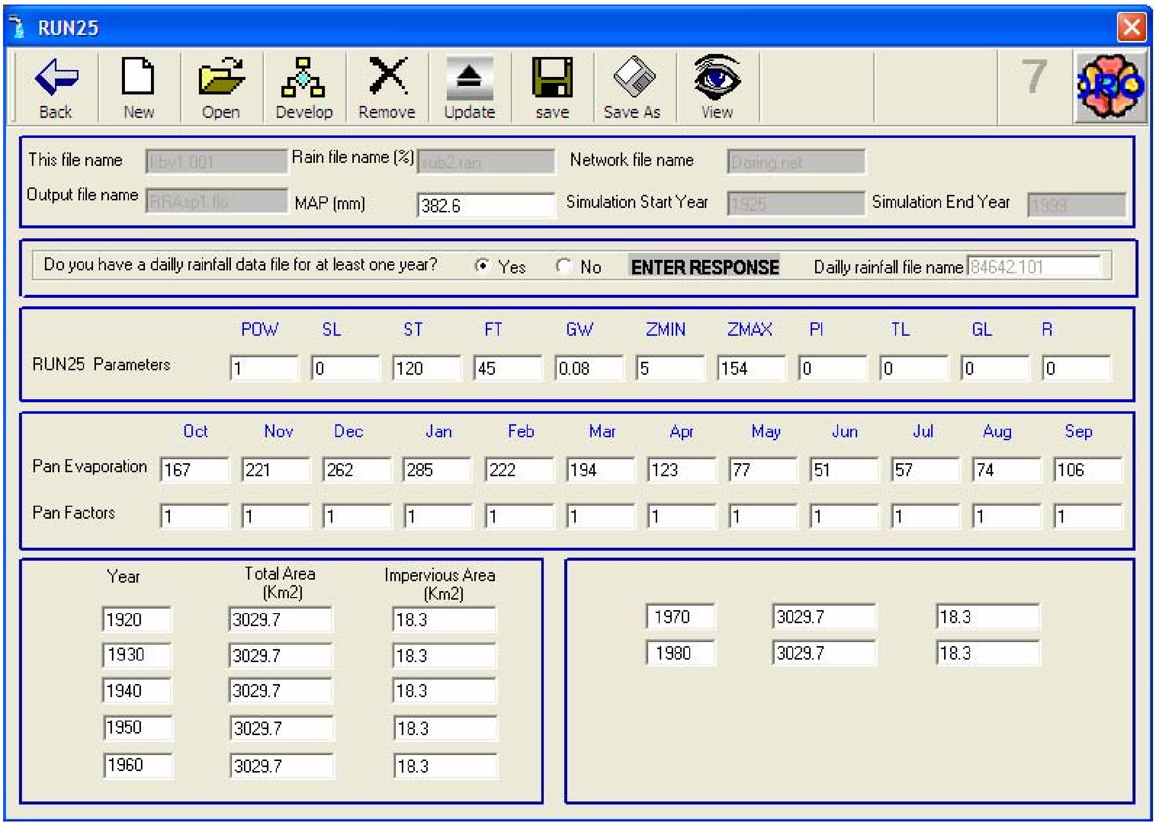
1.2.4 RUN25 user interface

The module RUN25 runs in two instances, in the calibration module and in the main model simulation linked to other module routines. In the two instances, the module utilises a parameter file with data structured as shown in Table A1.2 below. The file entries are discussed later in Section 1.2.5 of this Appendix in more detail.

Table A1.2 An example of RUN25 parameter file inputs.

Entry in parameter file	**Description**
1,"Run5.001"	Name parameter file for the module
2,1	Module location
3,"drn-01.txt"	Rainfall file name
4,"Yes","sub34flow2.101"	Daily rainfall file to use
5,400	Mean annual precipitation
6,2,0,200,30,0,0,180,1.5,.3,0,0	Rainfall-Runoff parameters
7,147,200,241,271,197,178,105,65,46,52,64,91	Symon's pan evaporation
8,.8,1,1,1,1,1,1,1,1,.8,.8,.8	Evaporation factors
9,1920	Rainfall data record start and end year
10,1999	
11,1920	RUN25 module simulation record start and end year
12,1999	
13,2	Number of stages in defining catchment
14,1900,1294,0	Year, pervious catchment area, impervious catchment area
15,1950,2121,0	

The data in the parameter file, such as that shown in Table A1.2, are entered using the RUN25 parameter input interface. Modifications or editing of values in the file will be achieved in the parameter-input interface and the CAL25 interface during calibration. The user can access the RUN25 user interface only when the network file opened in the main interface has a RUN25 module specified. A water resources network can have several sub-catchments where rainfall-runoff simulations are required such that the network file may have a number of the RUN25 modules specified to represent these rainfall-runoff simulations. The user should move the yellow highlighter to the RUN25 module that he/she wishes to edit or enter new parameters. When the sub-routine number corresponding to the RUN25 module is highlighted, clicking the Edit button will open the RUN25 parameter file input interface. New parameter values can then be entered in the parameter input interface, as well as a daily rainfall file (if available) and data on the extent of the pervious and impervious areas in the catchment in any year with data that lie within the simulation period, starting in the simulation start year. Input boxes indicating the start and end of the simulation are shown in the second row of input boxes in Figure A1.4.



This file name libv1.001
Rain file name (%) sub2.ran
Network file name Doring.net
Output file name RRAsp1.flo
MAP (mm) 382.6
Simulation Start Year 1925
Simulation End Year 1999

Do you have a daily rainfall data file for at least one year? ● Yes ○ No **ENTER RESPONSE** Daily rainfall file name 84642.101

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
RUN25 Parameters	1	0	120	45	0.08	5	154	0	0	0	0

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Pan Evaporation	167	221	262	285	222	194	123	77	51	57	74	106
Pan Factors	1	1	1	1	1	1	1	1	1	1	1	1

Year	Total Area (Km2)	Impervious Area (Km2)
1920	3029.7	18.3
1930	3029.7	18.3
1940	3029.7	18.3
1950	3029.7	18.3
1960	3029.7	18.3
1970	3029.7	18.3
1980	3029.7	18.3

Figure A1.4 RUN25 user interface.

1.2.5 The RUN25 module inputs

The inputs in the interface for the RUN25 module consist of text boxes and option buttons. The inputs can be entered by clicking option buttons, typing new values in text boxes that can receive text and, in the case of the disabled input boxes, values are entered through code procedures, triggered by events on the form. Figure A1.4 shows the RUN25 interface with examples of inputs.

The input boxes of RUN25 with parameter file entries as shown earlier in Table A1.2 are discussed here using the captions in the labels on the left of most input boxes and in the top row for monthly inputs and parameter inputs as shown in Figure A1.4.

This file name: The name of the parameter file that is currently opened is displayed in this input box.

Rain file name: The name of the file with the long series of monthly rainfall data in percentages of the mean annual precipitation is entered in this input box. The rainfall file can contain up to 110 years of monthly values. The name of the file is passed to the module interface when the form is loaded. The rainfall file is the input file 1 in the main user interface.

Network file name: The name of the network file defining the water system model structure is entered in this box. The file name is loaded when the form is loaded.

Output file name:The name of the main output file, with the monthly flow values generated from the rainfall is entered in this input box, on form loading. Entry of the output file name is done in the main user interface as the "Input file 4" for the RUN25 module.

MAP : The Mean Annual precipitation in millimetre values is entered in this input box. The value is directly typed into the box. The MAP value works with the rainfall data in percentages of MAP. The rainfall percentages are multiplied by the MAP value to give actual rainfall for each month in millimetre units for use in the model.

Simulation Start Year: This entry is the year in which the RUN25 module will start simulating. The value is entered on pressing the update button.

Simulation End Year: The year in which the simulation will end will be displayed in this text box when the update button is clicked.

Option Buttons: The option buttons work together with the daily rainfall file entries. If a file with the necessary daily rainfall data for the catchment being modelled is available in suitable format in the working directory, then the "Yes" option button is clicked. If no daily rainfall input is to be used for the RUN25 sub-routine being modelled then the "No" option is selected. In both cases, after clicking the appropriate option, the label captioned "Enter Response" is clicked. If the "Yes" option was clicked then the "Open file" dialogue box pops up, where the filter to open files of the extension ".002" can be used to open the daily rainfall file. If the "No" option had been selected then on clicking the "Enter Response" label, the file name box for the daily rainfall file is cleared and the "NO" option is recorded in the parameter file.

Parameters:

***POW*:** Power of soil moisture runoff equation. Equation A1.12 shows how this parameter is used in the model. This parameter has no units.

SL: Soil moisture storage level below which no runoff from the soil occurs. The value is in millimetres.

ST: Maximum soil moisture capacity in millimetre units.

FT: Runoff from soil moisture at full capacity in units of millimetres per month (mm/month).

GW: Maximum groundwater runoff in mm/month.

Zmin: Minimum catchment absorption rate in mm/month. This is Z_1 in the Equations A1.5 to A1.10.

Zmax: Maximum catchment absorption rate in mm/month. In the calculations the value is given as Z_3 as shown in the Equations A1.5 to A1.10

PI: Interception storage in millimetres. The amount of water that does not reach the ground and is considered to be lost through evaporation and evapotranspiration while trapped in leaves or other material covering the ground.

TL: Lag of runoff other than that from soil moisture. TL is the value K in the muskinghum Equation A1.16 for surface runoff.

GL: Lag of runoff from soil moisture. GL is the K value in the muskinghum Equation A1.16 when applied to ground water contribution to surface runoff.

R: The parameter defining evaporation-soil moisture relationship. The Equation A1.11 utilises the parameter R to determine catchment evaporation.

Evaporation:

There are two sets of evaporation inputs: the monthly pan evaporation values in millimetre units in the first interface row with 12 input boxes, and the pan factors in the second row. Monthly evaporation inputs as well as other monthly inputs, including monthly data files, are entered in the model starting in the month of October and ending in September for each year. The period starting in October and ending in September was used in the model to coincide with the hydrological year in South Africa. The South African hydrological year period starts at the beginning of the rainfall season in October and ends at the end of the dry season in September. In the pan evaporation input boxes other monthly evaporation figures, not necessarily pan values, can be entered if the model user considers them more representative of the stream-flow evaporation in the catchment he/she will be working on. The pan factor values are the monthly fractions applied to the evaporation figures to determine the amount of the given evaporation figure that should be applied in the model for the RUN25 module. The pan factor values should be a value of 1 (equal to pan evaporation rate) or less.

Catchment area statistics:

The last set of inputs consists of three arrays of input boxes for entering the state of the catchment over time in years for each year that has available data. The entries should start in the year that the simulation is started or earlier. For each year the total area in square kilometres (km^2) is entered as well as the area of impervious surface. It will be noted that the impervious area, apart from representing the areas that are naturally impervious such as rock formations, will be used to represent the development of paved areas on roads, urban settlements and other infrastructure. This value is usually a very small percentage of the total catchment area but steadily increases with time as a result of increasing levels of development in the catchment.

1.3 CAL 25: The calibration routine

The model calibration in HYDRO25 aims to identify and obtain a set of parameters for a particular catchment under particular hydrological and land use conditions, which give the best fit between simulated and observed streamflow for a particular calibration period. The period used in the calibration depends on the record length of observed runoff, measured rainfall, land use and evaporation used in the simulation. The module CAL25, which is basically the RUN25 module with added functionality to improve the input parameters, is used for calibration.

1.3.1 Steps to access CAL25

(1) The model user identifies the RUN25 module that he/she wishes to calibrate by clicking on it in the main user interface. The yellow highlighter will come to the sub-routine number corresponding to this module.

(2) Clicking the "EDIT" button or pressing of the "Enter" key will lead the user to the parameter input interface for the module to be calibrated.

(3) With the RUN25 parameter input interface open, the user can open an existing parameter file if there is one previously saved for this module, or save a new parameter file. To identify the parameter file which was saved for the module, the "View" button is clicked while the module interface is open. A "View" window highlighting the current sub-routine number will appear showing the current parameter file name immediately to the left of the highlighted sub-routine number. Clicking “OK” or pressing the "Escape" key will unload the "View" window.

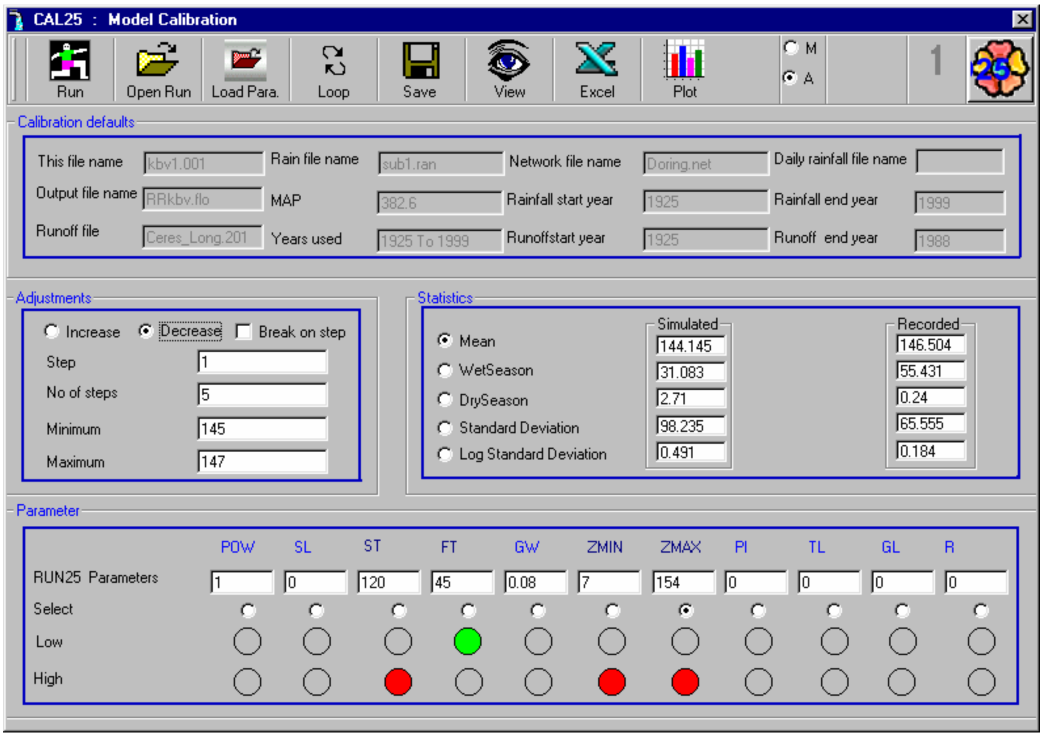
(4) After editing the parameter file, the parameter file is saved using the “Save” button or the “Save As” button if there is need to specify a new file name.

(5) With the module interface open, pressing the "Escape" key or clicking the "Back" button will take the user back to the main user interface.

At this stage the user will have defined the Runoff inputs, but the parameters in the rainfall-runoff modelling may not be suitable for the catchment characteristics. If recorded runoff for the catchment exists only for a few years, preferably longer than ten years, the user will need to use the naturalised flows to determine the most suitable parameter values, using CAL25. The term naturalised flows used here will refer to the flows at the virgin (undeveloped) state of the catchment, that is before any activities that modify the catchment hydrology have been implemented. The activities responsible for changing catchment hydrology include building of dams, deforestation, afforestation, developing of irrigation schemes and building human settlements.

1.3.2 Using CAL25

a) After editing and saving the parameter file and returning to the main interface as described in (1) to (5) immediately above, clicking the "CALIBRATE" button will open the CAL25 interface for calibration which is shown in Figure A1.5. The module highlighter should be corresponding to the RUN25 routine to be calibrated before the calibration button is clicked.



Calibration defaults

This file name: kbv1.001
Rain file name: sub1.ran
Network file name: Doring.net
Daily rainfall file name:
Output file name: RRkbv.flo
MAP: 382.6
Rainfall start year: 1925
Rainfall end year: 1999
Runoff file: Ceres_Long.201
Years used: 1925 To 1999
Runoffstart year: 1925
Runoff end year: 1988

Adjustments

○ Increase ● Decrease ☐ Break on step
Step: 1
No of steps: 5
Minimum: 145
Maximum: 147

Statistics

	Simulated	Recorded
● Mean	144.145	146.504
○ WetSeason	31.083	55.431
○ DrySeason	2.71	0.24
○ Standard Deviation	98.235	65.555
○ Log Standard Deviation	0.491	0.184

Parameter

	POW	SL	ST	FT	GW	ZMIN	ZMAX	PI	TL	GL	R
RUN25 Parameters	1	0	120	45	0.08	7	154	0	0	0	0
Select	○	○	○	○	○	○	●	○	○	○	○
Low	○	○	○	🟢	○	○	○	○	○	○	○
High	○	○	🔴	○	○	🔴	🔴	○	○	○	○

Figure A1.5 CAL25 user interface with examples of inputs.

b) In the Calibration interface, Figure A1.5, the button captioned "Load Para" is clicked to load the parameter file that will be used for calibration.

c) To open the file with the naturalised-recorded runoff the button "Open run" is used. The data file should be of the HYDRO25 monthly data format a sample of which is shown in Figure A2.5 of Appendix 2 as. If the file is not of the correct format an error message is generated which is cleared by clicking its "OK" button.

d) The rainfall-runoff simulation will run on clicking the "Run" button to generate monthly runoff in units of million m^3 per month. A statistical analysis of the simulated runoff is done, as well as a statistical analysis of the recorded runoff. The following statistical results are recorded on the user interface for comparison.

(i)	Mean:	The mean annual runoff for the period
(ii)	Wet Season:	The average of each year's highest monthly value
(iii)	Dry Season:	The average of each year's lowest monthly value
(iv)	Standard deviation:	The standard deviation of annual values
(v)	Log Standard Deviation:	The logarithm of standard deviation of annual values.

It should be noted that the recorded flow data used must lie within the same period as the period being simulated such that simulated monthly flows and recorded data for the same months are compared.

(e) The statistical parameter to be fitted to the recorded data are identified by clicking on the option button behind it. The order in which the statistical values are arranged from top to bottom is the order of importance that the developer attached to each parameter and also relates to the amount of influence the parameter accuracy has on the simulated flows.

(f) On clicking the statistical parameter's caption button, a comparison of the simulated and recorded data's parameters is done and possible changes are suggested for increasing or decreasing values of certain runoff parameters. These will be shown at the bottom of the user interface. A red circle indicator shows that if the value of the parameter is reduced then the statistical indicator of the simulated flow will get closer to the corresponding recorded flow indicator. If the parameter value is still in a reasonable range, for example, if it is not already zero, then the user is advised to reduce it. The yellow circle indicator shows that if the parameter is increased then the simulated data statistical indicator selected is likely to get closer to the recorded flow statistical indicator.

Using the statistics indicators and parameter box: The suggestions on varying the runoff parameters are not 100 % accurate due to several factors, that include:

(1) Quality of the input data

(2) Many factors that are not supported in the model such as soil types, the slope of the terrain, extent and type of plant cover on the land, and type of the rainfall storm.

(3) The complicated relations between parameters. Each statistical indicator's value depends on a combination of several of the RUN25 parameters.

The model user is advised to concentrate on changing the runoff parameters ST, FT, Zmin and Zmax, which can be identified by the captions in a deeper blue font. Other parameters should only be changed with caution.

The user will notice that when using runoff data that have very little relationship with the catchment, or when starting with unrealistic parameters, then the calibration suggestions will not behave as expected. Direct inputs of parameter values in the boxes is possible if large differences in parameter values need to be tried. In this case one can change all parameters at once, but should not forget to save the changes before running the model. The "looped" run button should not be used when several parameters are being changed, rather a single run is performed by clicking the button captioned "Run".

(g) To run the automatic calibration looped runs, the "Increase" or the "Decrease" option button in the adjustment box is selected to increase or decrease selected parameter values, respectively. "Break on step" selection box is selected to be able to see the new values of statistical indicators at the end of each simulation step before the set objective is met.

(h) On the left of the text box marked "Step", the extent of the increase or decrease step by which the selected parameter will be varied for each simulation loop is entered. Looped runs should be started with small values to check the sensitivity of the statistical values to the change in the runoff parameter value.

(i) The number of times that the step process will be done is entered in the text box with the label "No of steps". The value should be a positive integer.

(j) The maximum and minimum statistical indicator value is entered to define the range where the user wishes to see the statistical indicator value falling within.

(k) The button captioned “Loop” will start the looped run on clicking.

(l) If the user had selected to "break on step", then the module will run for a single step and display a message indicating that it has completed step 1. Clicking the "OK" button in the dialogue box will allow the looped run to proceed to the next step.

(m) Additional loops can be run by first saving the current parameter values by clicking"Save" to use the file at this stage, or by pressing the "Reload para" button then selecting the statistical indicator to be used, then the parameter to vary and the increase or decrease button. If other values in the adjustment box are not varied, then the previous entries as displayed in the boxes will be used. The user is advised that after a reload, selecting the statistical indicator button will give suggestions on changes related to the previous run with different parameter values to the ones that will be reloaded. Performing a single run after reloading the parameter file is advisable, to ensure that all statistical indicators shown relate to the reloaded parameter file.

Using the adjustment box: The computer will read the value of the decrease and increase option buttons to see what the user wishes to do with a selected parameter. If the user has selected to increase the parameter, then it will use the value defined in the step to increase the selected parameter, for example Zmin. For each new Zmin value the application will simulate the flow using all other values as in the last saved parameter file and include the new Zmin value. For each simulation step, the model will check if the new statistical indicator is within the chosen range as defined by the maximum and minimum values in the adjustment box. If the statistical indicator is within the range for any time step the model will stop and advise the user that it has found a value within the required range. If the statistical indicator remains outside the range, the model will continue to do the rest of the steps and at the end show the output of the closest match that it simulated as the last output. Parameter values displayed on the form are not saved until the "Save" button is clicked. Only parameter values that have been saved are used to start a simulation. The parameter file has to be saved after a looped run to accept the new value of the parameter and use it for further looping or, if the parameter values displayed are not required, then an existing parameter file is reloaded without changes. Use the button captioned "Load para" to reload the last saved parameter file.

Simulating looped runs: Changing the parameter values by only typing new values without saving and then running a looped run, will result in the use of the last saved parameter file excluding the changes. The displayed values are not changed except for the parameter that is being varied for the looping, such that the parameters displayed and those used in the run will be different. Further complications arise when the user clicks on the statistical indicators. The model will suggest the parameters that need changing but the values displayed will be wrong. The user is advised to avoid the problem by using the "Save" button or the "Reload para" button before any run. A single run will always display the parameter values of the last saved file.

CAL25 has hidden text boxes that display the changes that occur in each of the statistical indicators during a looped run. The text boxes are displayed during a looped run. They will show the changes at each step if the "Break on step" selection box is selected in the adjustment box. If the looping is done without breaking, then the values will be shown at the end of the run after all the looping has been done.

1.3.3 CAL25 tool buttons and other controls

The CAL25 interface, Figure A1.5, has a number of buttons in the toolbar control and on the interface form. The buttons can achieve a number of functions as described below:

(1) "**Back**": allows the user to return to the main user interface. This can also be achieved by pressing the "Escape" key or the flower icon on the top right hand corner of the form.

(2) "**Run**": will perform a single simulation of the runoff and statistically analyse output runoff. If a recorded file has also been opened it will also be analysed such that the two sets of outputs of statistical indicators can be compared.

(3) "**Open Run**": On clicking, a pop-up dialogue box will appear for opening existing files with the extension ".201". This file type should contain the recorded monthly runoff data in million m^3 starting in October and ending in September for all the years in the HYDRO25 monthly data format. The recorded runoff data used for comparison must be naturalised. The comparison takes place between the simulated flows that do not account for developments in the catchment, such that the output flows will be those that describe a virgin catchment.

(4) "**Load para**": this button will load the existing parameter file. If on clicking this button a message box pops up indicating that the file you are using was saved for another RUN25 sub-routine, it is advisable that the user leaves CAL25 and goes to the RUN25 module interface at the same sub-routine that he/she wishes to calibrate. In RUN25 the user should open the file to be calibrated and resave it with a different name, then return to the calibration routine. The parameter file used for calibration should be saved specifically for that RUN25 sub-routine, except in cases where a single runoff gauge is being used in the calibration for all the RUN25 sub-routines that are using the same parameter file. Calibrating a parameter file being used in more than one sub-routine means that all the other sub-routines will also use the parameter values calibrated using recorded flows that may not apply to all of them. It is important that runoff records for each sub-catchment are obtained and used in calibration.

(5) "**loop**": this button allows the model to do a number of runs, changing one of the parameters for each run as defined by the user.

(6) "**Save** ": this button will save two files, a parameter file with all the values as currently displayed, and a network file to include any modifications that the user will have done. The message "Saved" will be displayed in the top tool-bar control for any successful saving. It will be noted that this module does not have a "Save As" facility and thus will not allow the user to change the file name. File name changes can be done in the RUN25 module user interface.

(7) "**View**": On pressing this button or the "Enter" key, a pop-up form will be displayed showing the whole network/system and, most importantly, the parameter file that is currently saved for the sub-routine being calibrated. The current routine is displayed in the "View" window with its routine number highlighted in red, positioned in an accessible location. Immediately on the left of the sub-routine number will be the parameter file being used. To exit from the "View" window click the "OK" button in the window or press the "Escape" Key.

(8) "**EXCEL**": Clicking the button provides a link to the Microsoft Excel application. In Excel the entries of the simulated and the recorded monthly flows are recorded in columns suitable for drawing a graph for visual comparison of the monthly flows. After a simulation that includes the analysis of the recorded flows, clicking the “Excel” button will display an “Open file” dialogue box with a filter to show the Excel files only. The file HYDRO25.xls, which should be in the same directory as the data files, can be opened for updating. The file contains a prepared graph for the recorded and simulated flows. The values in the graph are updated. The model does not make any other changes to the Excel file that is opened except entering recorded and simulated flow values in sheet 1 of the opened file, HYDRO25.xls. A different file name can be used if required. In both cases, the final output file name will have a different name from the file that was opened for update, for example the file name HYDRO25.xls will generate a new file with the name HDRO251.xls. The file will need to be saved if required for later use or if the file chart has to be edited.

(9) "**PLOT":** The button works in co-ordination with the option buttons captioned "A" and "M". After a model run in the CAL25 and the selection of either option "A" for an annual plot or "M" for a monthly plot, clicking on the "Plot" button will load the line graphs of the recorded flow and simulated flow.

(10) The last three boxes in the Tool-bar: On the extreme right is a flower icon with the word "HYDRO25" scrolling. This control can be clicked to return to the main user interface. The box on the second position from right displays the sub-routine number. The third box from right is usually empty but displays the message "Saved "on completion of a successful save and will show the word "Running" when running a looped run if the "Break on step" selection is selected.

1.4 RES25: Reservoir simulation

1.4.1 General information on RES25

The module RES25 simulates the quantity of water stored in the catchment. The catchment water storage can be an existing dam or a "dummy dam", or a non existent dam that has been proposed for development. The "dummy dam" refers to an imaginary combination of several dams, such as small farm dams that cannot be included easily as single dams in the model. The module RES25 allows the user to enter up to 19 modifications to the storage over the simulation period. Modification can be done on the full supply capacity (FSC), dead storage capacity (DSC) and the dam surface area at FSC. The time-related modifications will allow for the inclusion of structural changes such as raising a dam wall and construction of new farm dams, as well as other time-related changes such as dam siltation and desilting exercises. In RES25 a water balancing process is maintained where inflows and outflows are simulated in relation to changes in the storage volume.

1.4.2 Theoretical and mathematical concepts in RES25

In the module RES25, a water balance equation that is a special case of the general control volume equation is used. This general control volume equation is called the Reynolds Transport Theorem (Chow, 1959).

Reynolds Transport Theorem

Reynolds Transport Theorem states that: "The total rate of change of an extensive property of a fluid, dB/dT is equal to the rate of change of an extensive property stored in the control volume plus the net outflow of the extensive property through the control volume" (De Laat, 1998). Equation A1.21 in Box A1.1 gives this relationship.

$$\frac{dE}{dt} = \frac{d}{dt}\int\int\int BpdV + \int\int Bp(U.dA) \quad \text{……………………….……..Equation A1.21}$$

Box A1.1 Reynolds Transport Theorem (De Laat, 1998).

In Equation A1.21,

E = extensive property of the fluid which depends on mass present (kg)
B = the intensive property of the fluid whose value is not dependent on mass (dimensionless)
p = density of fluid (kg/m^3)
V = volume (m^3)
U = velocity vector of the fluid (m/s)
A = area (m^2)
t = time (seconds)

U.dA is the vector dot product of the velocity vector of the fluid, U, with length (De Laat, 1998).

The Reynolds Transport Theorem gives the integral equation of continuity from which the water balance equation is derived. The integral equation of continuity was conceived from the following ideas:

If mass is the extensive property being considered then E = m and B = dE/dm = 1. By the law of conservation of mass, dE/dt = dm/dt = 0 because mass cannot be created or destroyed. Substitution in Reynolds Theorem yields the equation of an unsteady flow with variable density as given in Equation A1.22 which gives Equation A1.23 if the flow density remains constant.

$$0 = \frac{d}{dt}\iiint pdV + \iint pU.dA \text{ ....Equation A1.22}$$

$$0 = \frac{d}{dt}\iiint dV + \iint U.dA \text{ ....Equation A1.23}$$

Box A1.2 Applying the law of conservation of mass to the Reynolds equation (De Laat, 1998).

The integral, $\iiint pdV = S$, the volume of the fluid stored in the control volume, such that the first term in the Equation A1.23 is the rate of change of the storage with time, dS/dt.

The second term in the Equation A1.23 is the net outflow that can be split into inflow, I(t) and outflow, O(t). In the inflow, the direction of the velocity vector U and the area vector, dA, point in different directions such that their dot product is negative. In the case of outflow the vector dot product is positive. As a result Equation A1.23 can be represented as Equation A1.24 below.

$$\frac{dS}{dt} + O(t) - I(t) = 0 \text{ ....Equation A1.24}$$

The Equation A1.24 is the basis for the water budget concept used in the module RES25. The Equation A1.24 is also referred to as the mass balance or water balance equation (De Laat, 1998). In the Equation A1.24

I = Inflow (m^3/month)

O = Outflow (m^3/month)

$\frac{dS}{dt}$ = Rate of change of storage with time in (m^3/month) of considered control volume in the system. The control volume in RES25 is the volume of water in the dam.

Equation A1.24 requires that the system boundaries be well defined; since the boundary will be the region where the water balance is applied. Figure A1.6 gives the schematic illustration of how the water balance is applied in the RES25 module.

In RES25 the inflows, I(t) are:

(1) Direct rainfall (million m^3)

(2) Runoff entering a physical dam or "dummy dam" (million m^3)

The Outflows, O(t) are:

(1) Evaporation (million m^3)

(2) Seepage (million m^3)

(3) Releases (million m^3)

(4) Spillage (million m^3)

(5) IFR: In-stream flow Requirements (million m^3)

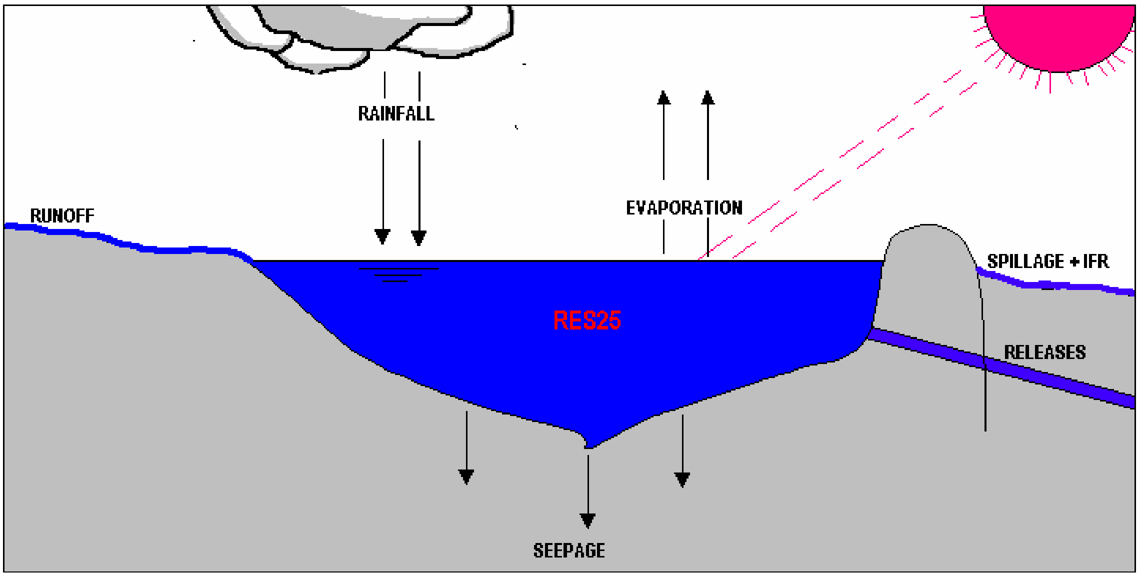


Figure A1.6 Illustration of the RES25 module concepts.

The inflow in the module RES25 are calculated using the Equation A1.25.

$I = R + P$...Equation A1.25

Where:

I = inflow (million m^3/month)

P = precipitation (million m^3/month)

R = runoff flowing into the dam (million m^3/month)

Calculation of outflows is done using Equation A1.26

$O = Ev + Sg + Rs + Sp + IFR$ ……………………………………...Equation A1.26

Where:

O = outflow (million m^3)

Ev = evaporation (million m^3)

Sg = seepage losses into the ground (million m^3)

Rs = controlled releases for downstream users such as irrigation (million m^3)

Sp = dam Spillage (million m^3)

IFR = instream flow requirements (million m^3)

Evaporation

Open water evaporation is calculated in the model using Symon's pan evaporation data figures. The evaporation data are factored using the monthly factor values that are entered. If there is no need to factor evaporation data values then monthly factors of 1.0 should be entered to retain all the original evaporation data. The volumetric evaporation is obtained by multiplying the depth of evaporation and the storage surface area after all the other dam outflows have been deducted in that month. The surface area is determined using the Equation A1.27 based on the work by Tarboton, Lecler, Smithers, Schmidt, and Schulze. (1995).

$A = bV^c$ ……………………………………………………….….Equation A1.27

Where:

A = surface area (m^2)

b = coefficient of the surface area/volume relationship (dimensionless)

V = volume at full supply capacity (m^3)

c = exponent of the surface area/volume relationship (dimensionless)

The model user will be able to enter values of b and c, that best describe his or her own catchment storage/surface area relationship. The values for b and c can be obtained by analysing dams with storage and surface area that are similar to the one being modelled. Default values have been provided in the model, these are 7.2 for the coefficient b and 0.77 for the exponent c. The values are based on studies done in the ACRU Model development (Tarboton *et al.*, 1995). A value of 0.6 is recommended for the coefficient c for small farm dams in the Water Resources Simulation Model developed by Pitman and Kakebeeke (1993).

Seepage

The seepage losses for unlined or earth dams can be estimated to give a more realistic overall reservoir yield simulation. In RES25 an estimate of the percentage of the available water volume that seeps out of the dam can be entered as an input value. The value is used in the model to calculate the amount lost as seepage. Tarboton *et al*. (1995), gave an estimate of 0.0006 of the full supply capacity of the dam as the daily seepage which is fixed throughout the simulation period. In the ACRU model seepage is estimated to empty the storage once every five years. In the module RES25 a default value of percentage monthly seepage is given. The default seepage loss value in RES25 can be used in cases where more accurate values that are closely related to the catchment in question cannot be found. In the model, if a zero value is entered or the input box for the percentage seepage is left blank, then the model will use a value of 0.001 % of month end volume as seepage, which is included within the code. This figure is not used if a valid percentage seepage value is entered.

Releases

The model calculates two possible sets of controlled releases from each dam according to the water demand files added to the water system by the model user. Equation A1.28 gives the two controlled release components.

$$Rs = R1 + R2 \qquad \text{Equation A1.28}$$

Where

Rs = total controlled releases passing through an outlet pipe or other controlled outflow route (m^3)

R1 = monthly releases due to water demand in "Input file 2" added to the main user interface for the dam (m^3)

R2 = monthly releases due to water demand given in "Input file 3" in the main user interface (m^3)

Total releases are provided when the water is available, after allocating water to the in-stream flow requirements, IFR. Releases are also restricted by the monthly "Target Draft" values that are entered in monthly input boxes labelled "Target Draft" in the RES25 module interface. If the "Target Draft" values are chosen to be used then the water allocated to "release", Rs, and to "IFR" will not exceed the target draft in each month even if water is spilling. A higher priority of water allocation is given to the IFR flows, such that water is supplied to satisfy all the IFR requirement before it goes to the controlled releases. A selection to use the target draft values can be made by clicking the text reading "Target draft", where the change in the label's background colour indicates that the target draft option will be used. If the "Target Draft" option is not selected the model will try to satisfy the total water demand Rs. Failure to meet the demand will be due to the inadequacy of water as determined in the water balance for the dam.

Spillage

Spillage calculation is done in the model using Equation A1.29

$S_p = V_p - FSC$ ……………………………………………………...……..Equation A1.29

V_p = Water volume at the beginning of the month (m^3)
FSC = Full supply capacity of storage (m^3)
S_p = Spillage volume (m^3)

IFR

The National Water Act (Republic of South Africa, 1998) considers the aquatic ecosystem to be an integral part of the (water) resource base from which water is derived for human and environmental use, but "only that water required to meet basic human needs and maintain environmental sustainability will be guaranteed as a right, which is now known as the Reserve" (Jooste and Claassen, 2001). The environmental or ecological aspect of the reserve has been identified in such a way that it must ensure water quantity and water quality which are appropriate to meet these needs. The term “resource quality” is used to include the health of all parts of the water resource, which together make up an ecosystem, including plant and animal communities and their habitat" (DWAF, 1997).

The term in-stream flow requirements (IFR) is used in this study to define the estimate of water required to maintain environmental sustainability of the river system downstream of a reservoir. In the model HYDRO25, IFR is represented by the Equation A1.30 below:

$$IFR = Fy(V) + Fx(I) \text{ ....Equation A1.30}$$

Where:

V = Storage volume at the end of the month, excluding excess water that will be lost as spillage (million m^3/month). V is calculated before all defined water demands such as urban and irrigation demand have been deducted.

Fx = Percentage of available volume that is allocated to IFR even when there is no water flowing into the dam (%)

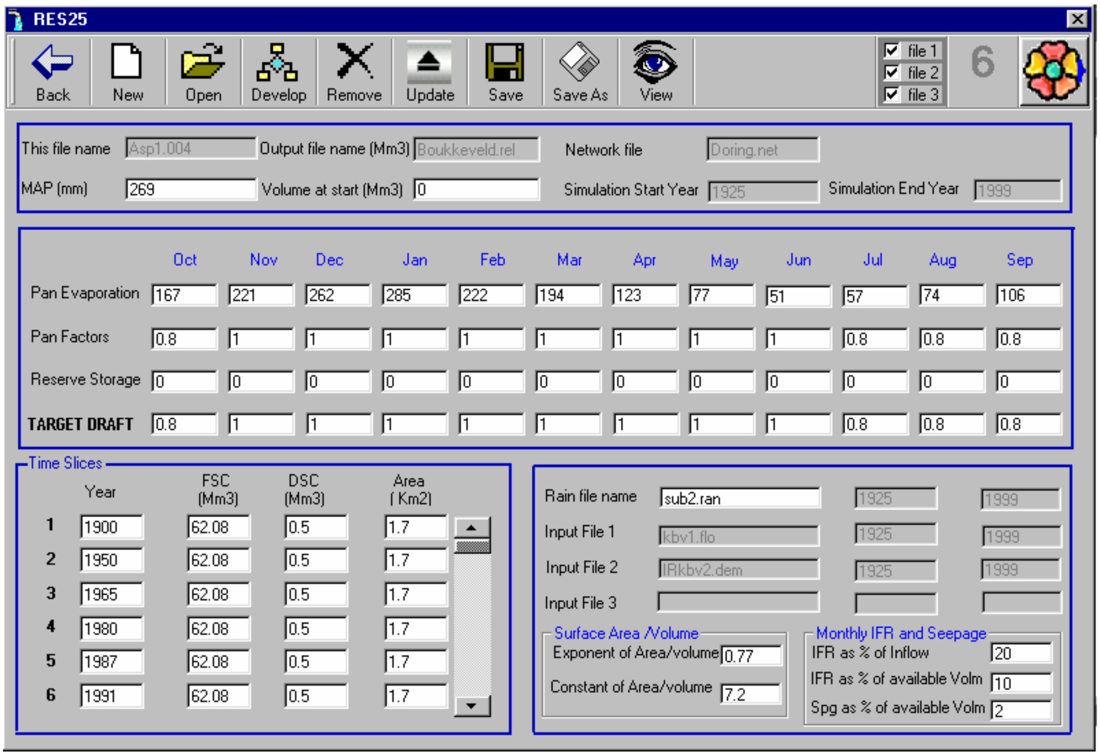
I = Total monthly volume of water that flowed into the dam (million m^3/month)

Fy = Percentage of monthly total water inflows that is allocated to IFR (%)

The values used for Fx and Fy should be determined on the basis of the catchment's ecological classification giving specific IFR requirements for a river reach or estimates based on other considerations of the aquatic ecosystem. The model has default values of Fx = 10 %, which is based on the work done in the model HYECO (Dube, 1999) and Fy = 20 % which was derived from the average of the IFR rule curve values used in a previous study of the Doring River (McKenzie Schafer and Venter, 1990)

1.4.3 RES25 user interface

The RES25 user interface, shown in Figure A1.7, is used to enter data and parameters that will be used when the model runs the RES25 sub-routine. Most of the input boxes in the interface are text boxes. The boxes that appear with a grey background on the screen cannot have text entered directly by typing in them, but rather rely on coded inputs within the interface to enter specific values.



This file name: Asp1.004
Output file name (Mm3): Boukkeveld.rel
Network file: Doring.net
MAP (mm): 269
Volume at start (Mm3): 0
Simulation Start Year: 1925
Simulation End Year: 1999

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Pan Evaporation	167	221	262	285	222	194	123	77	51	57	74	106
Pan Factors	0.8	1	1	1	1	1	1	1	1	0.8	0.8	0.8
Reserve Storage	0	0	0	0	0	0	0	0	0	0	0	0
TARGET DRAFT	0.8	1	1	1	1	1	1	1	1	0.8	0.8	0.8

	Year	FSC (Mm3)	DSC (Mm3)	Area (Km2)
1	1900	62.08	0.5	1.7
2	1950	62.08	0.5	1.7
3	1965	62.08	0.5	1.7
4	1980	62.08	0.5	1.7
5	1987	62.08	0.5	1.7
6	1991	62.08	0.5	1.7

Rain file name	sub2.ran	1925	1999
Input File 1	kbv1.flo	1925	1999
Input File 2	IRkbv2.dem	1925	1999
Input File 3			

Exponent of Area/volume: 0.77
Constant of Area/volume: 7.2
IFR as % of Inflow: 20
IFR as % of available Volm: 10
Spg as % of available Volm: 2

Figure A1.7 RES25 user interface with input examples.

RES25 inputs:

(1) MAP: Mean Annual Precipitation value of the sub-catchment in which the dam is located. The value will be used in conjunction with the average percentage rainfall files to calculate the actual rainfall values in million m^3 per month.

(2) Volume at start: This is the amount of water in million m^3 at the beginning of each simulation. This value will be used once as the starting value in the first October month of the simulation period.

(3) Pan evaporation: The first row of 12 input boxes with the caption "Pan evaporation" on their left are for monthly evaporation inputs. In these input boxes the twelve long-term average monthly Symon's pan evaporation values, starting in October and ending in September, are entered. The values will be used throughout the simulation. The unit of pan evaporation data in the module is millimetres.

(4) Pan factors: These are monthly inputs for factors that will be used to reduce the extent of the evaporation in each month. A value of 1.0 will ensure that the evaporation in that month will be equal to the amount given by the pan evaporation. The pan evaporation gives a potential evaporation in the area. Detailed assessments of actual evaporation in specific catchments have indicated the need to use pan factors lower than 1.0 in some months of the year (Green, 1985; Midgely, Pitman and Middleton, 1994). Values of pan factors obtained for the whole of South Africa by Midgely *et al*. (1994) are recommended for use if Symon's pan evaporation data given in their report titled "Surface Water Resources of South Africa - 1990" are used.

(5) Reserve storage: The 12 monthly inputs define the amount of water in million m^3 that should remain in the dam in any simulation year. A value of zero will ensure that the DSC only is used to define the water remaining in the storage.

(6) Target draft: The monthly target draft values define the upper limit of the possible abstraction in each month. The value consists of releases and the IFR water in million m^3. The target draft values are used only when the caption "Target Draft" is clicked, such that its background is turned to a cyan colour. The model will attempt to satisfy all the targeted draft requirements. If there is not enough water to meet the target draft requirement, then only the available water is sent to (partially) satisfy this requirement.

(7) Time Slices box entries: The box has sets of three input box arrays for entering the different storage states, for up to 19 time "slices" on an annual basis over the simulation period. The time slices will be for the years with data on FSC, DSC and the storage surface area values. If the values are available for most of the years in the simulation, it will be important to spread 19 sets of these values over the whole simulation period. The buttons captioned "Develop" and "Remove" are useful in entering new arrays. If only one set of values is entered say in 1900, then this set of values will be used for all the years that come after 1900. Time "slices" values must start in the first year of simulation.

(8) Rain file name: The name of the file with the monthly rainfall data as percentages of MAP is entered here. In the model, rainfall files are not created within a run and have to be available in the data file when any of the sub-routine interfaces is being used. The RAIN25 module that is accessed from the main user interface is used to generate the appropriate rainfall files. Appendix 2, Section 2.1.2 of this report, gives a description of how the rainfall files are generated in RAIN25. In the rain-file name input box, the user can enter the file by double clicking the input box to display an "Open file" dialogue box that will be used to specify the appropriate file. A better entry method is available, which includes the update function. Using this method, the input files that currently exist in the computer are selected in the selection boxes in the top tool-bar control. Then the update button in the tool-bar control is clicked. A pop up dialogue box for opening the rainfall file will appear where the file will be opened and the update of the rest of the files will immediately follow. Update of files in the model refers to the entering of the start year of data and the end year of data in files as well as entering the start year of the routine simulation and its end year. The "Open file" dialogue filter will favour the opening of a file with the extension ".ran". maintaining this file extension for the rainfall file names improves the file opening process as the "Open file" dialogue box will always suggest to the user the files with the extension ".ran" if he wishes to open a rainfall file. Suggestions in the "Open file" dialogue box ensure that the correct files are opened each time.

(9)Input files: The names of the files in the input boxes captioned "Input file 1" to "Input file 3" are provided from the main user interface. If a file entered for these input file boxes is not stored in the computer then the user must ensure a file with exactly that file name is generated in an earlier simulation, before this routine is simulated. In such cases an update of data in that file will not be required and this information is conveyed to the computer by not clicking the selection button corresponding to this file in the tool-bar control.

(10) Surface area/Volume: The box is for entering the exponent and the coefficient in the surface area volume equation, Equation A1.27, where default values are provided based on studies done in the development of the ACRU model (Tarboton *et al*., 1995).

(11) Monthly IFR and Seepage: The In-stream flow requirement is defined using two components: (a) a fraction of the total monthly inflow defined by the entry in the topmost input box and (b) a fraction of the end of month storage volume, excluding the amount of water that will spill. Default values for the two IFR components that are used in the simulation if the model user does not specify other values are given in Section 1.4.2 of this Appendix. The third input box is used to enter the fraction of water that will be lost through seepage. The value is entered as a percentage of storage available at the end of each month. The values in this section are based on informed estimates derived from the catchment being simulated.

The tool-bar control commands

Most command buttons in the RES25 user interface are located at the top of the form in the tool-bar with the exception of the "Target Draft" command button. The command buttons are discussed from left to right in the following section, with the caption on each command button being used to distinguish it from its neighbours.

Back Clicking the "Back" button loads the main interface window to replace the current window as the active window displayed on the computer screen. This function can also be achieved by clicking the flower icon on the right or pressing the "Escape" key. If changes had earlier been made in the current RES25 user interface then these changes will be lost when the "Back" button is clicked.

New Whern clicked, the "New" button will remove the monthly values for the following variables: pan evaporation, pan factors, reserve storage and target draft.

Open Clicking the "Open" button will display an “Open file” dialogue box where the user can specify which existing file he/she wishes to open. The file will be of the extension ".004". On opening the file, the data in the file and the parameter values will be entered in appropriate input boxes.

Develop The “Develop” button loads a new array of input boxes for defining storage development over the years of the simulation.

Remove The time slice array which was added last will be removed when the "Remove" button is clicked. This is the only way to remove the arrays that will have been added to the time slices. Deleting array values and leaving them blank when saving a parameter file gives problems when the application runs. The application will expect values in all dynamically loaded text boxes. Unused dynamic input boxes, such as time slice input points created using the “Develop” button, should be removed using the "Remove" button before running the application.

Update The "Update" button is used to determine the current start and end year of the data set in the input files that the user will have entered for the sub-routine in the main user interface, as well as the rainfall file. To use the button, the selection boxes corresponding to the input files should be selected by clicking in them, if that file already exists on the computer. Clicking the "Update" button without selecting the files with data will only update the rainfall file. The files labelled "File 1 to 3" may be files generated in another routine of the same simulation, in which case they will not be updated when the “Update” button is clicked. The "Update" button will also determine the start year and end year of the RES25 simulation routine.

Save	The “Save” button will save a file that has been opened using the “Open” command if it has not been modified. The button will not work if there is no currently open file, or if there have been modifications on the opened file that may require the file to be renamed, or if the program suspects that some changes have been made that require a file to be resaved with a different name. The model will suspect that there is a need for a parameter file name change if the user opens a parameter file that was used for another routine or if he changes the names of other input files such as rainfall and flow files working with the module.
Save As	The "Save As" button allows the user to save a file with a different name or to overwrite an existing file. The values that are currently displayed will be saved through a “Save file” dialogue box. When saving, the model requires that the update button be clicked to ensure that any other changes pertaining to start and end years of the sub-routine simulation are still correct for the files in use.
View	Clicking the “View” button displays the network structure showing all the sub-routines and, most importantly, the parameter file name for the present routine. This file name will be located immediately on the left of the sub-routine number that will be highlighted in red colour. This function can be achieved by pressing the “Enter” key and it works for an existing network file where the current sub-routine exists in the network, which is possible only if the RES25 routine at the current position as defined by the routine number has been previously saved.

1.5 CHAN25: Wetlands routine

The module CHAN25 models water loss from wetlands due to evaporation, evapotranspiration and infiltration into the groundwater as well as the wetland area recharge.

The wetland area in CHAN25 is treated like a simplified RES25 storage. The simulated wetland area has a storage capacity to define the limit of water accumulation, a recharge coefficient to define the fraction of the inflows that contribute to the recharge, and a fixed monthly bed loss for losses due to infiltration. A CHAN25 routine should only be included in a water resources network in cases where there are wetland areas or a wetland area in the catchment in being modelled.

1.5.1 Theoretical and mathematical concepts in CHAN25

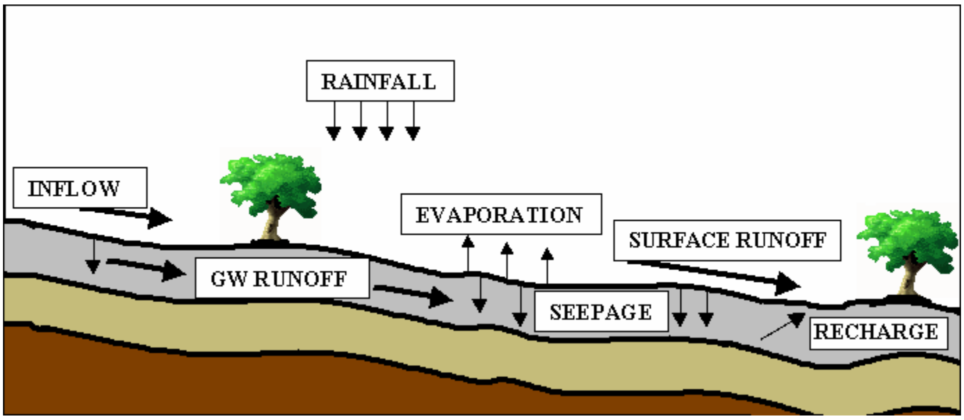


Figure A1.8 Schematic illustration of the CHAN25 sub-routine.

The water balance principles, discussed in Section 1.4.2 of this Appendix for the RES25 module, are used in the CHAN25 module. In CHAN25 the water balance equation, which is illustrated in Figure A1.8, is broken down into inflows and outflows that consist of the following components:

Inflows:

Rainfall

Runoff flowing into the wetland area (surface inflow)

Recharge from groundwater

Outflows:

Evaporation

Bedloss

Runoff flowing out of the wetland area (surface outflow)

Water balance components

Rainfall

A rainfall file is entered in the CHAN25 sub-routine to enable direct rainfall to contribute to the wetland area inflows. The rainfall contributing to the wetland recharge is calculated from Equation A1.31, below.

$$Rc = P \times MAP \times \frac{Aa}{1000} \quad \text{……………………………………………..……..Equation A1.31}$$

Where:

Rc = Direct rainfall contribution to the wetland area recharge (m^3)

P = Monthly rainfall values in % of MAP (dimensionless)

MAP = Mean Annual Precipitation (mm)

Aa = Wetland area (m^2)

In the CHAN25 module all rainfall falling on the wetland area can contribute to recharge.

Runoff into the wetland area

The amount of water available for wetland recharge is determined by factoring the runoff flowing into the wetland using the recharge coefficient (C). A coefficient of recharge is entered for the CHAN25 module as a positive proper fraction in the module's user interface. Equation A1.32 is used to calculate the runoff contribution to the wetland recharge.

$Ri = C \times Rin$ ……………………………………………….……….Equation A1.32

Where:

Ri = Total wetland area recharge (m^3)

C = Recharge coefficient (dimensionless)

Rin = Flow from surrounding area to the wetland area (m^3)

Evaporation:

Symon's pan evaporation values are entered in the model for each month in the CHAN25 module interface. Evaporation is determined in a similar way to the method used in the RES25 module with adjustments being made to the pan factors to indicate the difference in the amount of evaporation between open water in the reservoir and the wetland area. Other evaporation figures obtained using other methods which are not Symon's pan figures can be used in the model provided the appropriate evaporation pan factors that will represent the evaporation from the particular wetland are known and are included in the inputs. In cases where factoring of evaporation inputs is not required, a value of 1.0 for the pan factors is entered and if evaporation values that are larger than the Symon's pan evaporation are required pan factors greater than 1.0 are entered. In the model, the factor is simply multiplied by the evaporation figure to get a fraction of the evaporation that will be used for that month in all the years that will be simulated for the sub-routine. Equation A1.33 shows how evaporation is calculated in the CHAN25 module.

$Ev = Ep \times Ef \times Aa$ ……………………………………………….....Equation A1.33

Where:

Ev = Evaporation (m^3)

Ep = Pan evaporation (m)

Ef = Evaporation factor (dimensionless)

Aa = Wetland area (m^2)

The surface area of the wetland entered in the determination of evaporation does not vary with volume as with the case of a RES25 module, Equation A1.27. The depth component of the wetland area is very small such that surface area is usually directly proportional to the wetland volume. There is therefore no need to include a special relationship between the evaporation, the surface area and the depth of the wetland as is done in the case of dams.

Bed Loss

In the module CHAN25 fixed monthly values of Bed Loss are entered in m^3. The values should be determined from physical observations on the catchment or estimates based on previous values measured for similar catchments.

Wetland releases

A water balance is applied to the wetland such that the wetland storage equation, (De Laat and Savenije, 1998) is used to determine the amount of water released from the wetland. The storage equation applied for the CHAN25 module is shown as Equation A1.34.

$$O = I + G_w + \frac{dS}{dt} \qquad \text{...Equation A1.34}$$

Where:

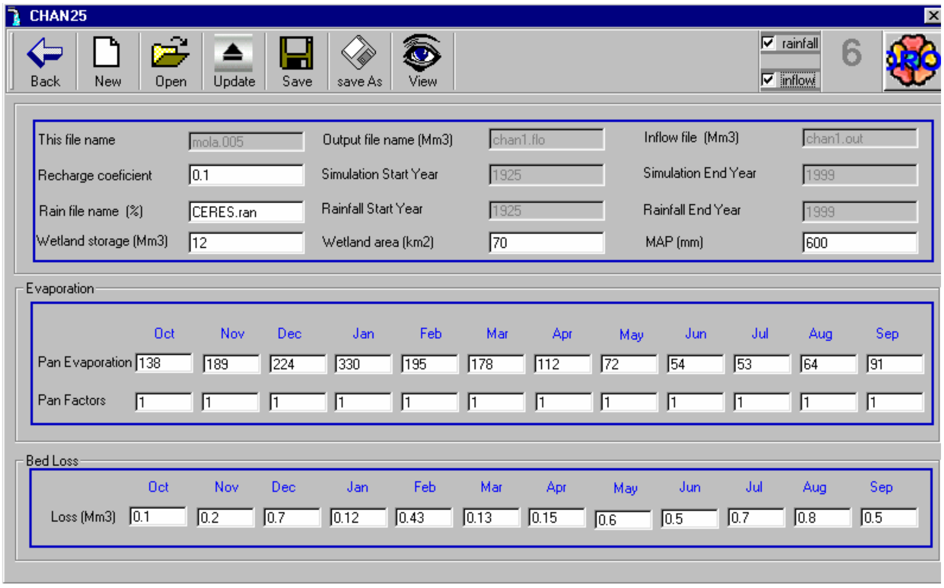
O = Releases from the wetland outlet (m^3/month)

I = Surface runoff flowing into the wetland and direct rainfall (m^3/month)

G_w = Ground water inflows (m^3/month)

$\frac{dS}{dt}$ = Rate of change of the wetland volume (m^3/month)

1.5.2 The user interface in CHAN25



This file name	mola.005	Output file name (Mm3)	chan1.flo	Inflow file (Mm3)	chan1.out
Recharge coeficient	0.1	Simulation Start Year	1925	Simulation End Year	1999
Rain file name (%)	CERES.ran	Rainfall Start Year	1925	Rainfall End Year	1999
Wetland storage (Mm3)	12	Wetland area (km2)	70	MAP (mm)	600

Evaporation

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Pan Evaporation	138	189	224	330	195	178	112	72	54	53	64	91
Pan Factors	1	1	1	1	1	1	1	1	1	1	1	1

Bed Loss

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Loss (Mm3)	0.1	0.2	0.7	0.12	0.43	0.13	0.15	0.6	0.5	0.7	0.8	0.5

Figure A1.9 User interface in CHAN25.

Figure A1.9 shows the user interface for the CHAN25 module. The interface has two sets of input boxes: enabled input boxes where values can be entered directly through typing in the required information, and disabled input boxes where values cannot be typed in. The disabled boxes receive values from code-defined procedures on loading of the user interface, followed by clicking the “Update” button, which opens and then saves a parameter file. The enabled input buttons are discussed in the following section with the names used to identify the boxes in the user interface being used as sub-headings.

(1) **Recharge coefficient:** The recharge coefficient is used in the model to factor the amount of flow entering the wetland area so as to determine the amount of water that will be available to recharge the catchment if wetland storage is not full. The recharge coefficient will be high for highly permeable sandy soils and low for impermeable clay soils.

(2) **Rain file name:** The name of the file with the monthly rainfall data in percentages of the MAP is entered in this input box. The input box is double clicked to select the name of the file through the "Open file" dialogue box that pops up. Rainfall files have to be maintained with the extension “.ran” for easier handling in the model.

(3) **Wetland Storage:** The volume of the wetland storage in million m^3 is entered in this input box. The value used as the catchment area storage is the limit of volume that the area can store, such that any additional inflows will be released without being stored.

(4) **Wetland area:** The value of the total wetland area in km^2 is entered in this input box. The amount identified as wetland area should be excluded from the total catchment area of the module RUN25 such that there is no double counting of runoff from the wetland area.

(5) **MAP**: Mean Annual Precipitation in units of millimetres is entered in this input box. When the model runs the MAP value is multiplied by the monthly rainfall percentages in the rainfall file to get monthly precipitation values in millimetres units.

(6) **Pan Evaporation:** Long-term monthly pan evaporation data are entered in the 12 monthly input boxes provided for evaporation. The values are entered in millimetres.

(7) **Pan Factors:** Twelve pan factor values corresponding to monthly evaporation values are entered in the boxes to calculate the fraction of the pan evaporation that will occur in the wetland area. If the whole depth of evaporation as given in the pan evaporation value will be lost in a month, then a value of 1, is entered for the factor.

(8) **Bed Loss:** Most wetlands lose some water through their beds to recharge ground water reserves such that this water is lost from the surface water system. To account for this water loss, fixed monthly bed loss values in million m^3 are entered for all months from October to September. In cases where such loss is not taking place the "zero" values are entered for bed loss.

The tool-bar controls.

The CHAN25 module uses basically the same buttons as those found in most of the other modules. All the buttons in the CHAN25 tool-bar control, with the exception of two, are discussed in earlier sections of this chapter under the user interface controls for the RES25 module, Section 1.4.3 of this Appendix. The two selection boxes, captioned, "Rainfall" and "Inflow" have not been discussed before. These selection boxes are selected for updating the two data files used in CHAN25. The rainfall data file should always be updated. A surface runoff file with the inflows may not be in the working directory at the time this module is saved in the network and its update will therefore not be required. Such a case occurs when the inflows to this module are a result of a simulation in another earlier module such as RUN25. Under these conditions this file will not need to be updated and its selection box should not be selected.

CHAN25 parameter file

Table A1.3 below shows CHAN25 parameter file inputs. The filename should ideally have the extension ".005". File name extensions of this nature were meant to assist the model user in recognising the parameter files that will be used at different stages of the simulation so that he/she will not end up selecting wrong input files for the different modules.

Table A1.3 An example of CHAN25 module parameter file inputs.

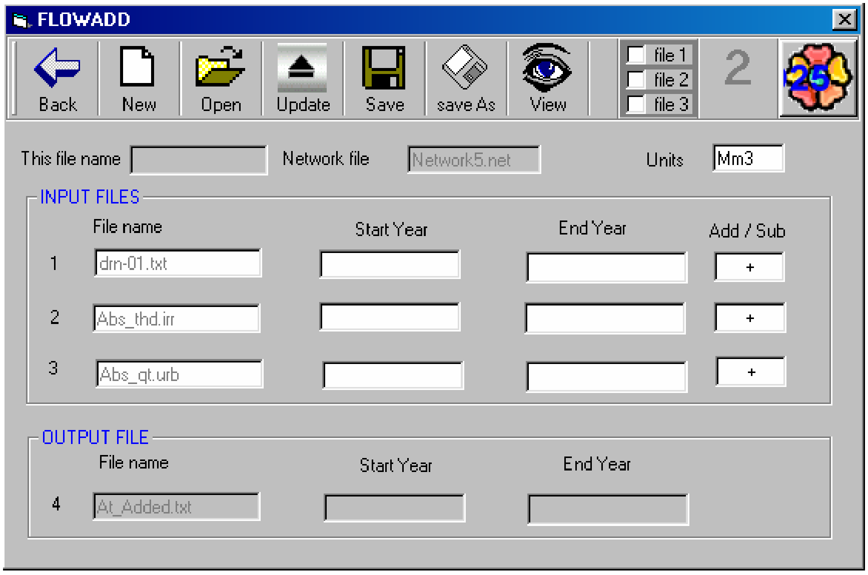
Entry in parameter file	Description
1,"channel9.005"	Name of parameter file for the module
2,5	Module location
3,"drn-03.txt"	File with data on inflows to wetland area
4,"DRN-01.ran"	Rainfall file name
5,450	Mean Annual Precipitation
6,1920	Year in which simulation starts
7,1984	Year in which simulation ends
8,1925	First year with rainfall data
9,1992	Last year with rainfall data
10,12,450,0.1	Wetland storage, Wetland area, Recharge coefficient
11,124,146,125,134,123,129,161,171,165, 143,124,161	Long term monthly pan evaporation in millimetres
12,.8,1,1,1,1,1,1,1,1,.8,.8,.8	Pan evaporation factors
13,.1,.2,.7,.12,.43,.13,.15,.6,.5,.7,.8,11	Bed loss in million cubic metres
14,#TRUE#	TRUE means a valid rainfall file name has been specified and is part of the data set

1.6 FLOWADD

The module FLOWADD is useful for the addition of data for up to three files that require summing during the simulation, or where subtractions are required. The data files that are added or subtracted in FLOWADD should be in the HYDRO25 monthly data format. An example of the use of this module is a point in the catchment system where runoff from a catchment has to be added to releases from a dam and outflows from a wetland area. The names of the files with the data, or output files which will have data after a simulation, are entered through typing them in or double clicking the appropriate input boxes in the main user interface as discussed in Section 1.1 of this Appendix. The filenames will be entered in the FLOWADD module when the module is loaded. Direct typing in of the file names is restricted in the module.

1.6.1 FLOWADD user interface

The module FLOWADD has a larger number of disabled input controls, 14 as compared to the enabled input controls, 4 input boxes and 3 selection boxes, as shown in Figure A1.10. The output file generated when FLOWADD is used will span the period covered by all the entry files. This is made possible by obtaining its start year from the input file with the earliest start date and then using the simulation end period taken from the file whose last year of data are most recent. The assumption is that the user will only enter data that he requires to be added up or subtracted, and cut out those data that should not be added or subtracted.



This file name
Network file: Network5.net
Units: Mm3

INPUT FILES

	File name	Start Year	End Year	Add / Sub
1	drn-01.txt			+
2	Abs_thd.irr			+
3	Abs_qt.urb			+

OUTPUT FILE

	File name	Start Year	End Year
4	At_Added.txt		

Figure A1.10 FLOWADD user interface with input examples.

An overview of input boxes in the FLOWADD module

A single mathematical equation is applied for each month in FLOWADD. The simplified equation is presented below as Equation A1.35

$$O_T = (O_1 \times F_1) + (O_2 \times F_2) + (O_3 \times F_3)$$ ……………………………….....Equation A1.35

Where:

> O_T is the resultant flow per month (m^3); O_1, O_2, O_3 are the monthly flows obtained from the input files 1 to 3; and F_1, F_2, F_3 are the factors used in the module code to represent the values entered for the input files 1 to 3 as the input in the corresponding "Add/Sub" input box. If the "+" (plus) value was entered for input file 1, then F_1 will be a "1", if a "-", (minus) is entered in the file 2, then F_2 will be "-1" such that the input file 2 is subtracted and if any other character is entered in the input box for file 3, then F_3 will have a "0", zero value, and will not be added or subtracted.

Disabled Input controls

Disabled input controls, where direct typing of data are not possible, are discussed below for FLOWADD.

This file name: The name of the file that is opened or saved for the current FLOWADD module will be shown in this box. The name is entered in the box on opening of an existing file of the extension ".003" or on saving a file with the inputs for the current FLOWADD module.

Network file: The box will receive the name of the network file that is currently in use for the system being edited. This input box should always have a value, which comes when the interface is loaded.

Input files: The input file names, the start and end years of their data, as well as the add or subtract functions to be used, are entered in the input boxes under the caption “Input files”.

The first column of input boxes under the heading “Input files” contain the input file names. The names are entered in the input boxes when the module user interface is loaded. The user should ensure that all the file names specified in the main user interface are shown in the controls before updating and saving the current file. If some boxes have no files then the user should exit the user interface and reload it using the "Enter” key or by pressing the "Edit" button.

The second and third column of input boxes under the “Input files” controls should contain the “Start” and “End” years of the data in each of the files to be added. The values are entered in the input boxes by pressing the update buttons after selecting the selection boxes corresponding to the files that currently have data. If a specified file does not have data, or if the data in the file are to be replaced by outputs from a module running earlier in the network, then this file should not be selected for updating.

Output file

A single output file with monthly data in the HYDRO25 data format is generated as the output file. The file name should be specified in the main user interface. The start and the end years of the output file are displayed on clicking the “Update” button if the files named as file 1 to file 3 contain data.

Enabled input boxes

The FLOWADD module has four enabled input boxes. There are three controls in the column titled "Add/Sub" which are input files. In these boxes, the following can be entered:

(a) "+" to specify that this file should be added.
(b) "-" to specify that the file should be subtracted
(c) " " a box left blank will not be added or subtracted; it is left out of the calculation. Any other character will also have the same meaning as the 'blank'.

The module FLOWADD has three selection controls. The selections are made by clicking in the selection control corresponding to a file with data. If a file has no data and the file is to be created earlier in the network before this sub-routine, then the selection box corresponding to this file is not selected for update.

An input box for entering units is provided, the units entered will be used for the output file of the sub-routine. A default value of "Mm^3" (million cubic metres) is available for the units box.

1.6.2 The tool-bar control in FLOWADD

The buttons in the tool-bar control are mainly the general buttons used in RUN25 and RES25 as discussed in Section 1.4.3 of this Appendix. Use of the selection boxes explained above is not as critical as its use in the RUN25 and RES25.

1.6.3 FLOWADD parameter file

Table A1.4 below shows an example of a FLOWADD routine parameter file inputs. The file is saved together with a network file every time the "Save" or the "Save As" button is used while the module parameter input interface is being used. The file should ideally have the extension ".002".

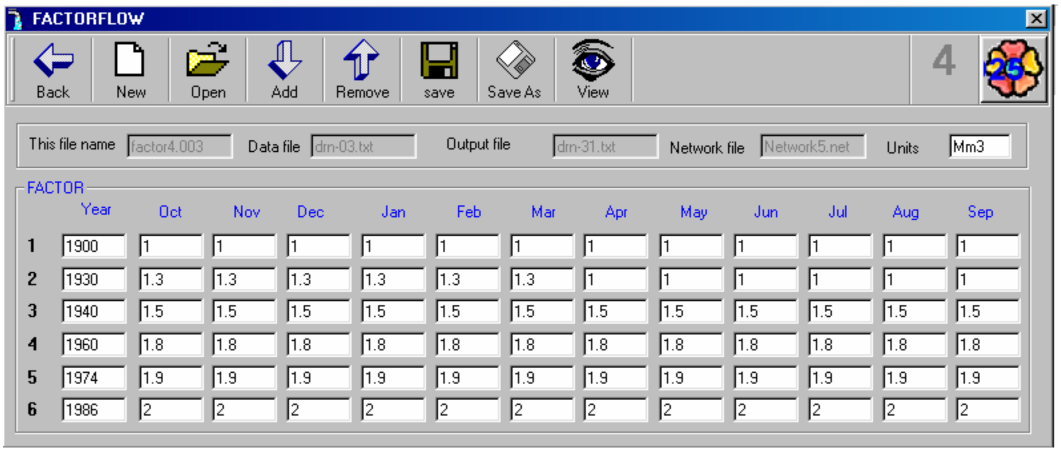
Table A1.4 An example of the FLOWADD parameter file inputs.

Entry in parameter file	Description
1,"Add8.002"	Name of parameter file for the module
2,2	Module location
3,"drn-01.txt",1920,1999,"+"	List of names of files whose data are to be added or subtracted, the beginning and end years of the data in the files, the symbol "+" for additions or "-" for subtraction
4,"Abs_thd.irr",1920,1985,"+"	
5,"Abs_qt.urb",1936,1994,"+"	
6,"At_Added.txt",1920,1999	
7,"Mm3"	Units of data in the file (million cubic metres is the default value)

1.7 FACTORFLOW

The module FACTORFLOW allows a single monthly data file to be factored, using monthly factors covering up to ten time steps extended over the duration of the input data file. A typical example of a situation where this module is used is when the abstraction from a reservoir to an urban area, or the inflows from a mining area, have to be increased with time due to growth or expansion. Critical growth stages are determined and factors applied to account for this growth in the output file. The factors are applied in block periods, that is if a factor of 1.2 is entered for October 1920 and the next factor for October, 2.4 is in 1930 then, for the period 1920 to 1929 the 1.2 factor is used and the 2.4 factor will start to be applied in 1930. The start year for entering factors should be smaller or equal to the start year of the data in the data file that is being factored.

1.7.1 FACTORFLOW user interface



This file name: factor4.003
Data file: drn-03.txt
Output file: drn-31.txt
Network file: Network5.net
Units: Mm3

FACTOR

	Year	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
1	1900	1	1	1	1	1	1	1	1	1	1	1	1
2	1930	1.3	1.3	1.3	1.3	1.3	1.3	1	1	1	1	1	1
3	1940	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5	1.5
4	1960	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8	1.8
5	1974	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9	1.9
6	1986	2	2	2	2	2	2	2	2	2	2	2	2

Figure A1.11 FACTORFLOW user interface with examples of module inputs.

An overview of the input boxes

The input boxes shown in the user interface, in Figure A1.11, are discussed below with the captions used in the interface being used as the sub-heading. The input boxes discussed in (1) to (4) below are not enabled; that is, inputs cannot be typed in directly.

(1) **This file name:** The name of the file with the data for the module is entered in the box. The file extension ".003" is supported by the FACTORFLOW module and a file filter to restrict files available for opening uses this extension.

(2) **Data file:** The name of the file with the data that will be factored is entered in this input box. The file should be of the HYDRO25 monthly input data format and is usually a flow data file. The file name is entered in the box on loading of the module "FLOWADD".

(3) **Output file:** The name of the output file that the user will have specified in the main user interface is entered in the input box on loading of the user interface.

(4) **Network file:** The filename of the water resources network, is entered in the box on loading of the user interface. A network file should always be displayed when a

module is being edited. If the network file input box does not have the name of the network displayed, then the form should be closed and then reloaded.

(5) **Units:** The specific output data units are directly entered into the text box by typing in the value. This value is not used when the module FACTORFLOW is run; it is only displayed in the output file as additional information on that file.

(6) **Factor box:** In the box titled "Factor" an array of input boxes with ten rows and thirteen rows can be created using the "Add" button located in the tool-bar at the top of the user interface. In the array of input boxes the monthly factors to be multiplied by the monthly data in the data file are entered. The button captioned "Remove" is used to remove the last row of input boxes that will have been added to the array of input boxes. Unused rows of input boxes should be removed before saving the module parameter file.

1.7.2 Tool-bar control in FACTORFLOW

The buttons in the tool-bar control are basically the same as those discussed in the module RES25, in Section 1.4.3 of this Appendix. The "Add" and "Remove" buttons have images of arrows to indicate what happens at the end of the arrays of input boxes when the button is clicked. The "Add" button will add a row of input boxes, and the "Remove" button will remove a row of input controls at the end of the array.

1.7.3 FACTORFLOW parameter file

The file that is saved in the FACTORFLOW module user interface is referred to as the FACTORFLOW parameter file. The filename should ideally have the extension ".003" and should contain values as shown in Table A1.5, below. It is not advisable to make changes to the parameter files directly using text applications such as text pad or notepad. Procedures defined in the model will enter changes made to the parameter files into other files required for running the programme, such as the network file, if parameter entries are made in the user interface. If other applications are used to update the parameter files then the updates will remain incomplete. The process of making changes will take very little time if done within the model interfaces and will ensure that errors are not carried through to the process of running the model, where errors may waste the model user's time.

Table A1.5 An example of FACTORFLOW parameter inputs.

Entry in parameter file	Description
1,"factor4.003"	Name of parameter file for the module
2,"drn-03.txt"	Name of file whose data are to be split according to specified factors
3,4	Module location
4,"Mm3"	Units of data in the file
5,5	Number of years with data on how flows should be factored
6,1900,1,1,1,1,1,1,1,1,1,1,1,1	Year and the factors to be used in that year and up to the next year with factors
7,1930,1.3,1.3,1.3,1.3,1.3,1.3,1,1,1,1,1,1	
8,1940,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5,1.5	
9,1960,1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8,1.8	
10,1974,1.9,1.9,1.9,1.9,1.9,1.9,1.9,1.9,1.9,1.9,1.9,1.9	
11,1986,2,2,2,2,2,2,2,2,2,2,2,2	

1.8 IRRIG25: Irrigation module

1.8.1 General functionality

The module IRRIG25 simulates the water use due to irrigation requirements. The module generates monthly irrigation water demand that is received from the water system to meet crop evapotranspiration requirements. The module generates as an output a demand file which is applied as an abstraction from a reservoir using RES25, and from channel flow using FLOWADD and FACTORFLOW modules. The module also simulates return flows from irrigated areas.

1.8.2 IRRIG25 mathematical module structure

Water demand in IRRIG25 is calculated on a monthly basis using the Equation A1.36 below:

$$D = A_r \times P_a \times (fE_o - rR_o) \qquad \text{Equation A1.36}$$

Where

D = Volume of Demand (m^3)
A_r = Total irrigation area in that year (m^2)
P_a = Proportion of area irrigated in that month (dimensionless)
f = Crop factor (dimensionless)
E_o = Evaporation (A-pan evaporation) (m)
r = Effective rainfall factor (dimensionless)
R_o = Rainfall (m)

The module allows the user to enter the changes in area available for irrigation in hectares over the years, as well as the variation in the fraction of that area which is irrigated each month. Evaporation input data should be A-pan values. However, other evaporation types such as Symon's pan can be used, provided the appropriate crop factors are also used. Another monthly input is the effective rainfall to account for that water which is available for evapotranspiration and excludes the water which is lost before the crops can utilise it.

1.8.3 IRRIG25 user interface

The module IRRIG25 generates a water demand file and a return flow file that is calculated on the basis of the return flow percentage entered by the model user in the text box captioned "Return Flow %". The module uses a parameter file; a copy of the data in one such parameter file is shown as Table A1.6 below.

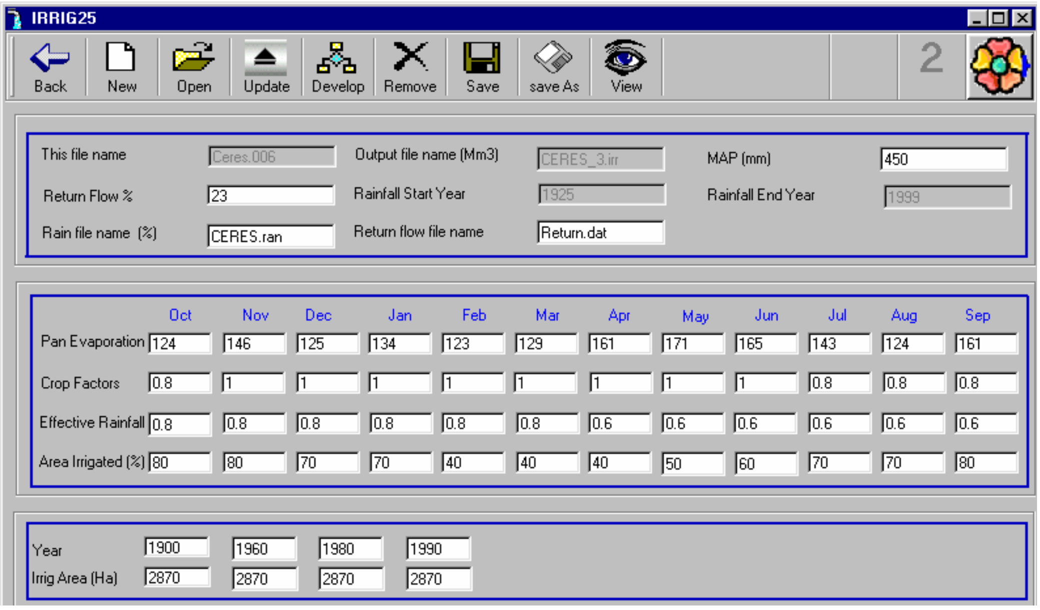
The parameter file contains the input data that the user enters for use when the module IRRIG25 is simulated. The parameter file data fills the input boxes in the user interface when the file is opened. A description of these entries is given in Section 1.8.4 of this Appendix. To edit or access an IRRIG25 module, the module must exist as part of the network being simulated or must be entered in the main user interface as a new module. After clicking on the IRRIG25 combo box, the “Edit” button is clicked and a new window, the module interface, will pop up. The IRRIG25 module interface is shown in Figure A1.12.

Table A1.6 An example of 1RR1G25 parameter file inputs.

Entry in parameter file	Description
1,"Ceres3.006"	Name of parameter file for the module
2,6	Module location
3,"23"	Return flow as percentage of irrigation demand
4,"CERES.ran"	Rainfall file name
5,450	Mean annual precipitation
6, 1925	Start year of rainfall data
7, 1999	End year of rainfall data
8,"Return.dat"	Return flow file name
9,"Nola.irr"	Irrigation demand file generated in simulation
10, 224,291,340,369,284,249,161,103,70,80,103, 146,124,161	A-pan monthly evaporation
11,.8,1,1,1,1,1,1,1,1,.8,.8,.8	Crop factors
12,.8,.8,.8,.8,.8,.8,.6,.6,.6,.6,.6,.6	Fraction of total rainfall that is effective rainfall
13,80,80,70,70,40,40,40,50,60,70,70,80	Percentage of total area that is irrigated
14,#TRUE#	True if the specified rainfall file has been found in the data directory
15,4	Number of years with irrigation area data
16,1900	Years with irrigation area data and the corresponding irrigation area below each year.
17,400	
19,1960	
20,1400	
20,1980	
21,1760	
21,1990	
22,1800	

1.8.4 1RR1G25 module inputs

Inputs in IRRIG25 are entered through the use of text boxes and clicking of command buttons in the tool-bar. The Figure A1.12 shows the IRRIG25 module interface with the text boxes and command buttons, as they will appear when the interface inputs are being edited.



This file name: Ceres.006
Output file name (Mm3): CERES_3.irr
MAP (mm): 450
Return Flow %: 23
Rainfall Start Year: 1925
Rainfall End Year: 1999
Rain file name (%): CERES.ran
Return flow file name: Return.dat

	Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
Pan Evaporation	124	146	125	134	123	129	161	171	165	143	124	161
Crop Factors	0.8	1	1	1	1	1	1	1	1	0.8	0.8	0.8
Effective Rainfall	0.8	0.8	0.8	0.8	0.8	0.8	0.6	0.6	0.6	0.6	0.6	0.6
Area Irrigated (%)	80	80	70	70	40	40	40	50	60	70	70	80

Year	1900	1960	1980	1990
Irrig Area (Ha)	2870	2870	2870	2870

Figure A1.12 IRRIG25 module user interface with examples of module inputs.

A discussion of entries to be made in each of the input spaces is discussed in the following sections using the captions that identify each input space as shown on the left of the input boxes and at the bottom of the command buttons in Figure A1.12.

(1) **This file name:** The name of the file with the data for the module is entered in the box. The file with the name extension ".006" is entered in the input box on opening of an existing file or on saving of a new file name for the sub-routine. The user is advised to click the "View" button or press “Enter” to see the file that the model is currently using if this module is not new in the system. If the module is new and has not been saved, then it will not be shown in the "View" window.

(2) **Output file name:** The name of the file that will contain the monthly water demand simulated by the IRR1G25 module.

(3) **MAP (mm):** mean annual precipitation for the area being considered in the irrigation module.

(4) **Return Flow (%):** The percentage that will be applied to the irrigation water demand to generate the return flows.

(5) **Rainfall Start Year**: The year marking the beginning of the records in the rainfall file.

(6) **Rainfall End Year**: The last year with rainfall data. It is noted that the rainfall file must cover the period being simulated. In cases where the period being simulated is

longer than the available rainfall file then the rainfall file must have "zero" values to fill the remainder of the rainfall file so that the rainfall file ends in the same year as the last year of the simulation.

(7) **Rain file name:** The name of the file with the catchment rainfall is entered here. In the model, rainfall files are not created within a run and have to be available in the data file before they are selected for use in network modules.

(8) **Return flow file**: a filename for the file that will contain the return flows isspecified here. The return flows are calculated on the basis of the irrigation demand and the percentage that the user applies as return flow fraction.

(9) **Evaporation and crop factors:** The model development used A-pan evaporation data in all irrigation calculations, and the model user should also use these evaporation values to simulate irrigation. The choice of A-pan evaporation was based on recommendations from previous studies such as (Green, 1985, Pitman and Kakebeeke, 1993; Kunz and Schulze, 1995) where A-pan evaporation was considered to be more accurate at representing crop evaportranspiration. The values are entered on a monthly basis, starting in October. The model user will notice that the A-pan evaporation values are larger than the S-pan evaporation values. If other types of evaporation data are used the crop factors applied must relate to the specific evaporation data in use. The crop factors describe the extent of water required for evapotranspiration by each crop in each month. The model uses average crop factors for more than one crop if a number of crops are grown in the irrigation area. The model user needs to determine the average crop factors for each irrigation area through the use of weighted factors where such factors relate to the area covered by each crop in each month. The crops that use more water in certain months have large crop factor values for those months. As an example, maize has crop factors as high as 1.3 in November in the Western Cape, whilst deciduous fruits in the same area and cabbages have crop factors as low as 0.2 for most months of the year.

(10) **Effective rainfall**: Twelve entry points are available for the model user to enter the fractions of the total rainfall that are available to the crops as effective rainfall in each month. Not all the rainfall recorded by rain gauges will reach the ground in all areas. Processes such as interception reduce the amount of rainfall reaching the ground such that only a certain fraction of the rainfall, referred to as "effective rainfall", is available for evaportranspiration. The model uses factors to calculate the effective rainfall. The factors usually range between 0.8 and 0.6 in most South

African catchments, other values below one can be accommodated by the input boxes.

(11) **Area irrigated:** the model allows the user to specify the area available for irrigation on an annual basis in hectares. A monthly variation of the actual area irrigated depending on the cropping patterns is entered in the column for the monthly inputs. To enter more values for the years irrigated the user should use the "Add" button to get new entry positions.

(12) **Tool-bar Control:** The command buttons on the tool-bar control and their functions are discussed in the RES25 module in Section 1.4.3 of this Appendix.

1.9 Graph

The model HYDRO25 has a built-in graph routine and a supporting user interface for the user to obtain a graphical presentation of input data files and output files. The graph routine is accessed from two interfaces, the main user interface and the rainfall-runoff calibration routine, "CAL25 ". The graphs drawn are time series graphs with two possible options of a monthly and an annual series.

1.9.1 Accessing the graph routine from the main user interface

The main user interface allows the user to graph any time series data file with values given in monthly time steps over at least two years of records. The file name should be available in the display on the main user interface as one of the files in the working directory. The following sequence of steps is followed to obtain a graphical illustration of the time series data:

(1) An option is selected for the type of graph to be drawn by clicking on the option marked "1" for monthly time steps and the second option for an annual plot. Figure A1.1 shows the option buttons on the main user interface.

(2) The specific file to be plotted is identified by clicking it to give it focus.

(3) In the task bar, the menu button "Graph" will immediately display the graph on clicking. The data file must be in the format used by the HYDRO25 model for monthly data.

1.9.2 Accessing the graph routine from CAL25 user interface

Two graphs are always obtained when the CAL25 user interface is used to draw graphs. In this case, the graphs are useful for the rainfall-runoff calibration. A time series graph of the simulated runoff is drawn together with the recorded data for the same period. The following steps are followed to use the CAL25 interface to give the graphical illustrations of simulated and recorded runoff:

(1) The rainfall-runoff routine, "RUN25", that is to be calibrated in the main user interface is selected by clicking the box with its name followed by the button captioned "Calibrate", to go to the calibration routine.

(2) In the CAL25 user interface, a single run or looped multiple runs are done as detailed in Section 1.3.2 of this Appendix on "How to use CAL25"

(3) Clicking the option button labelled "A" will select an annual plot and the option "M" will specify that a monthly plot is required.

(4) The task bar button captioned "Plot" is then clicked to show a time series graphical plot with default options on how the graph will look.

1.9.3 Graph resetting

The graphs obtained when accessing from the main user interface, and when using the calibration module as described above have the same user interface. This allows the user to change how the graph is shown and how it is printed. The illustration below, Figure A1.13, shows the interaction areas available for the graph and Figure 9.5 shows a typical annual hydrograph of recorded and simulated runoff. Descriptions of the available options are listed below according to the labels shown in Figure A1.13.

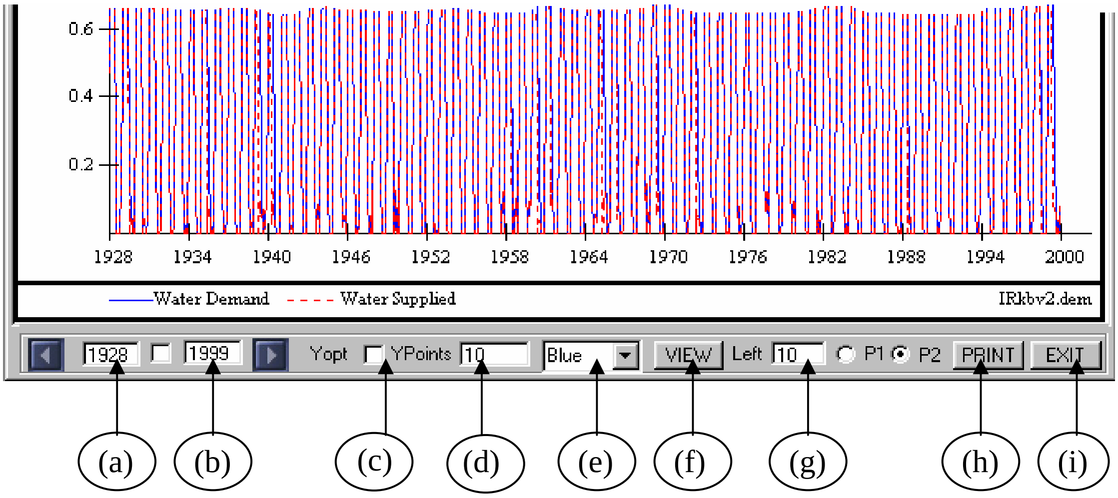


Figure A1.13 **Graph interaction area with points of interaction (described in the text below).**

(a) and (b) **Start Year and End Year**

These two values give the range of data being plotted as it will be shown on the X-axis. On the left will be the year that the plotting starts and the other value will be the year that plotting ends. The values that are displayed when the graph window pops out give the longest range possible with the data given; that is, the two years will be the first (earliest) year that has data and the most recent year with data. In the case of the CAL25 graph only the years that have data for both recorded and simulated runoff are drawn. The user can select periods shorter than the default values to give better view of certain sections of the graph. If the user selects non-valid periods, the default values are used; these are the values the graph uses when it is loaded for the first time.

(c) and (d) Yopt and Ypoints

The "Yopt" is a selection box that works with the "Ypoints" value. When the "Yopt" box is selected the user is able to give larger values in the "Ypoints" box which are used as the intervals on the Y-axis. As an example, entering 100 in "Ypoint" will give an interval of 100 on the Y-axis if the "Yopt" is selected. If "Yopt" is not selected then the "Ypoint" value gives the number of points to be given on the Y-axis, with a maximum of approximately twenty points and a minimum of five points. If a value lower than five points is selected, the default number of approximately ten Y-axis values is used. In the two cases, that is the case when "Yopt" selection is made and the case when the selection is not made, the maximum number of points on the Y-axis that will be equally distributed over the range of the values in the data files is twenty. Entries that may result in more than twenty points are not displayed. On the other hand the lowest number of points is maintained at approximately five with four and six points occurring if the graph routine finds them most appropriate in giving the best visual display that satisfies the data and options made for "Ypoints" and "Yopt".

(e) Colour box

The selection of colour uses a combo box with six possible colours. The colours selected apply to the single graph displayed if only one graph is displayed and to the simulated data plot if two graphs are being displayed. The recorded data line and the water supplied line are always dotted red lines.

(f) View

This view button should be clicked after any changes are made on the graphical interface options. The button refreshes the view with the changes made.

(g) Left

This text box allows the user to change the left margin alignment, a feature that is most useful when printing the graph. Integer values are entered in the text box followed by clicking the view button to shift the left alignment of the graph. The changes in the left alignment are not reflected in the right alignment, such that the overall effect is either a stretching effect or squashing of the X-axis. When a large left margin is required, a large integer is entered in the text box. The user can use multiples of ten for very large changes.

(h) and (i) Printer Option Buttons

P1 and P2 refer to the two possible options when printing. The option is selected before the Print button is clicked. The options allow two possible settings of printer outputs that affect the orientation of the axis and how the y-axis values are interpreted by different printers. Most printers use the default selection, but if the printer produces a distorted graph that has a different orientation from the one displayed on the screen, then P2 should be tried.

1.10 HYDMAP: The geographical information interface

1.10.1 General information on HYDMAP

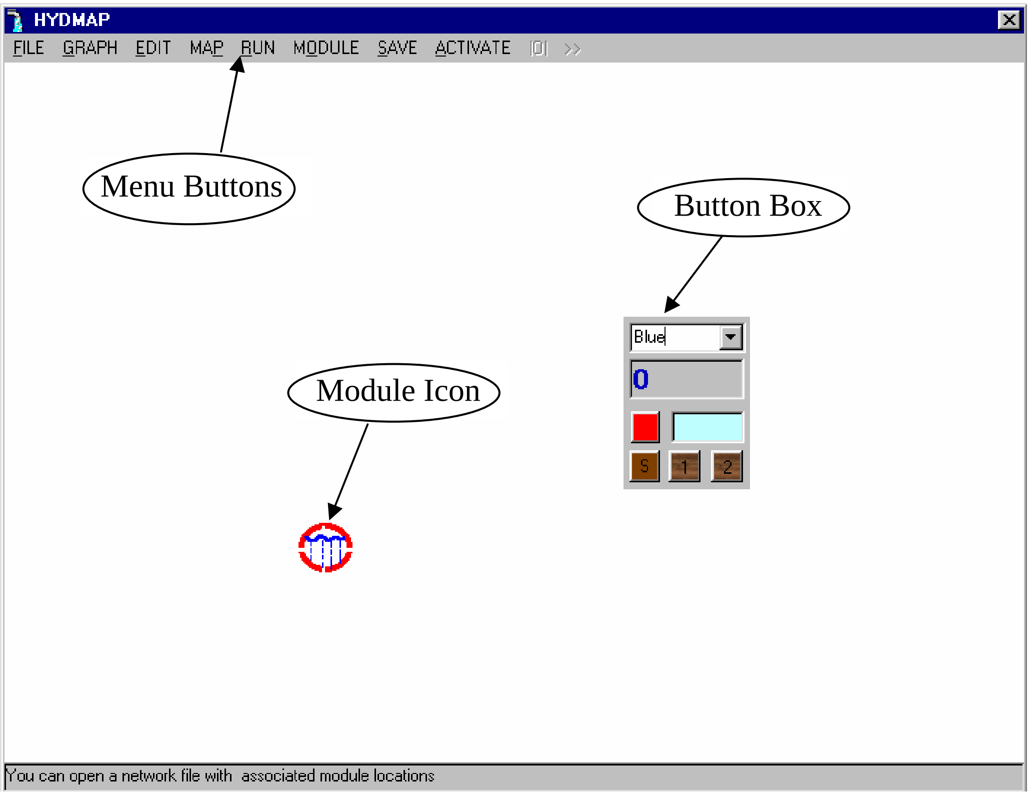
The module HYDMAP allows the use of graphics and maps to edit the model inputs and to illustrate or display the catchment simulation in a way that is closely related to the catchment's physical state. In this module the model user can work with an interface that is closely related to the mental picture of the catchment that he/she creates. The module uses a graphical interface to reinforce the understanding of commands and functions of interface objects, which reduces the requirement of high knowledge levels in model users. The command buttons have suggestive names and images that relate to the command button functions. The HYDMAP module uses graphical options to include some of the functions that are attached to the main user interface, such as organising the network modules, editing module data and drawing graphs of input and output data. In the HYDMAP interface the model user interacts with the model on a "Drawing board" where the catchment map can be included, as well as a drawing of the catchment network with points where the user can interact with the drawing.

The development of the HYDMAP module made it possible for the model to be able to read data from a number of image formats such that maps and graphics in several formats can be loaded to the “Drawing board” of the module. The module supports image formats that includes formats whose filenames have the following name extension ".jpg", ".bmp" and "ico".

On the map the model modules are represented by image buttons that the user can place at locations of his choice. The modules are linked using lines. Module inputs are edited and data files viewed using click events on the interface. The graphical network as displayed in the HYDMAP interface can be saved for later use.

1.10.2 The use of HYDMAP

The HYDMAP interface was developed with a large work space where the model user can add objects that describe his/her catchment as well as interact with these objects to enter data, edit model parameters and draw graphs of time series data. The interface has menu controls at the top, a button box in the open space, as well as an initial module as shown in Figure A1.14 below. A HYDMAP interface with showing the catchment map and modules is shown in Appendeix 2 as Figure A2.8.



You can open a network file with associated module locations

Figure A1.14 HYDMAP user interface before adding catchment modules.

1.10.3 Accessing HYDMAP

Access to the HYDMAP is handled by a menu button titled “MAP” in the main user interface. On clicking the “MAP” button the HYDMAP interface is loaded with a link to the main user interface network data. The link between the HYDMAP data and the data loaded in the main user interface is lost if the model users specifies a new path by opening a file saved in another location that is different from that of the data loaded in the main user interface. In the HYDMAP user interface, a number of menu buttons and a few command buttons are used to pass information from the user to the model. The interface interaction points are discussed in the following section.

1.10.4 HYDMAP FILE menu buttons

An illustration of the "FILE" menu button and its sub-menus is shown in Figure A1.15.

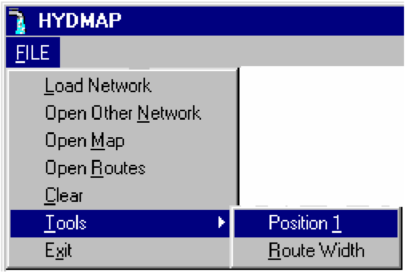


Figure A1.15 File menu buttons in HYDMAP.

The functions of the sub-menus under the "FILE" menu are described under each sub-menu title in the following section. The underlined letters in the names of the menus are used for quick access to the menu functions. To use the quick access the model user presses the "Alt" key of the keyboard and the underlined letter simultaneously.

Load Network : The "Load Network" sub-menu will load the network file that is currently open in the main user interface. If the network file has valid module inputs then the initial module icon is changed to that of the first module in the network. If the catchment network module locations were previously saved in the HYDMAP, then the model user has the option of opening the saved locations of all modules. This option is selected by clicking the "ACTIVATE" menu button. To avoid displaying all the network modules the "Clear" sub-menu button of the "FILE" menu is clicked. This allows the model user to place the modules at new locations one at a time.

Open Other Network: Clicking the button labelled "Open Other Network" will activate the "Open File" dialogue box where the user can open other network files including the one that may already be loaded in the main user interface. This button can also be used in cases where there is no open file in the main user interface. Clicking the "ACTIVATE" button before using this button allows the associated location file of the modules to be opened such that all the modules will be shown at locations that they were saved, in relation to a catchment map or other diagram that the model user will have loaded.

Open Map: The "Open Map" button allows the user to open a map image where the modules can be placed. It is not a requirement that a map is used for any network. The modules can be displayed in the white space and editing done from there if a map is not available or if the user wishes to develop a schematic catchment that is not related to a map.

Open Routes: Clicking the "Open Routes" button will open the file with data on the catchment routes and display these routes on the user interface.

Clear: The "Clear" button will clear the routes then activate a message asking the user if he wishes to clear the displayed modules as well. If the user answers positively by clicking the option marked "Yes", then the modules will be cleared from the display. If the model user clicks the "No" option, then only the displayed routes will be cleared. Clicking the "Clear" button will also set the file opening and reloading option to open network files without the associated modules and routes locations. Changing this option to allow opening of locations is done through the clicking of the "ACTIVATE" button.

Tool: The tool button handles the access to the sub-menus "Position 1" and "Routes Width"

Position 1: Clicking the "Position 1" button will set the button box to a default position allowing the model user to be able to work on it if it was not within his/her view.

Routes Width: Clicking the "Routes Width" will change the thickness of the displayed module routes. Only two sizes of widths can be selected by either clicking the button once or twice

Exit: Clicking the button "Exit" will unload the HYDMAP interface to return to the main user interface.

Graph menu button

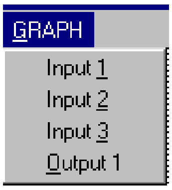


Figure A1.16 HYDMAP Graph menu button.

The "GRAPH" menu button (Figure A1.16)connects the displayed modules to the graph functions. Each module has at most three input files and a single output file whose names are entered in the main user interface. Time series graphs of the data in input files can be plotted on the computer screen or a printer by clicking one of the options, labelled "Input 1", "Input 2" and "Input 3", or the option labelled "Output 1" to print output file data. In the case of the RES25 modules, where the second input file is a water demand file, the graph will also plot the water supply file so that the model user can observe the periods when the simulation failed to supply all the water demanded. This failure to meet water demand usually shows points of water system failure, which is important information for decision-makers.

EDIT menu button

The button labelled "EDIT" allows the model user to access the module editing routines for the module selected before the "EDIT" button is clicked. To select a module and edit its inputs the user clicks the graphical icon representing the module and then clicks the "EDIT" button. A user interface where the module inputs and parameters can be edited will pop up.

MAP button

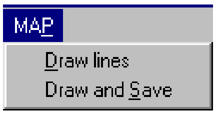


Figure A1.17 Map menu button options in HYDMAP.

The "MAP" button (Figure A1.17) provides access to the two sub-menus labelled "Draw lines" and "Draw and Save". On clicking the button "Draw lines" the user will be able to draw lines that can be used to represent map boundaries or routes connecting modules. These lines only exist on the screen and cannot be manipulated using commands such as those for varying the width. Saving of routes and other lines is possible only after the "Draw and Save" button is clicked. The data on the routes and line positions are stored in a file whose name is derived from the network file name with a changed file extension, where ".net" is changed to ".lin"

Module button

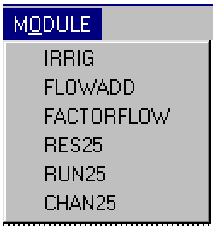


Figure A1.18 Module button options in HYDMAP.

Clicking a sub-option of the "MODULE" button (Figure A1.18) gives a description of the module functions and the module graphical icon at the position clicked by the user on the HYDMAP user interface immediately after clicking the module button. The description of the module function appears in the display control at the bottom of the window. The module icons are displayed only when there is no open network file in the HYDMAP interface. If there is an open network file then only the module description will be displayed.

SAVE button

Clicking the "Save" button will save the module locations. Saving of module locations is possible only if a network file has been opened by clicking either the "Load Network" or the "Open other Network" button of the "FILE" menu. The module locations will be saved in a file that has the network file name as well as the file name extension ".dat".

ACTIVATE button

The "ACTIVATE" button works with the two menu buttons with the labels "IOI" and ">>". The button labelled "IOI" is for locating a position on the user interface and the button labelled ">>" is for loading a network module icon to the interface. To change the position of a module icon the computer pointer is used to click the module icon, then the "ACTIVATE" button is clicked, followed by the button labelled "IOI", then the new position for the module is clicked. The module icon will move to this new position immediately. The button labelled "IOI" is also used to position the button box which is illustrated in Figure A1.14. To change the position of the button box the cyan coloured button in the box is clicked such that its colour changes to red which means that the positioning process is active on the button box. The next step is to click the position on the interface where the tool box should go to. Additional clicks on the positioning button in the button box will alternate between making the button box movements possible and allowing movements of the module icon that was clicked on or added last.

Load Button

Clicking the “Load” button with the “>>” label loads modules from the opened network file, one at a time. To load a module the “Load” button is clicked followed by clicking the position where the module will be located. When using the “Load” button the "ACITIVATE" button is clicked if the “Load” button is in a disabled state, that is the state when it cannot be clicked. The “ACTIVATE” button will enable the “Load” button. If the modules in the network are all represented by icons on the user interface then further clicks of the “Load” button will not load more modules, and clicking the "ACTIVATE" button at this stage will disable the “Load” button. The user is able to tell if the “Load” button is active or not from the style of the label, an embossed label means that the label is not active. In Figure A1.14 the “Load” button is shown in a disabled state.

Button box in HYDMAP

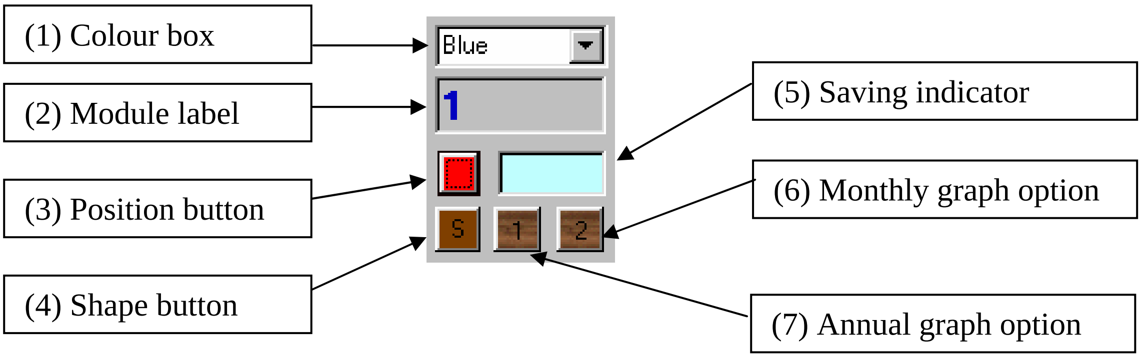


Figure A1.19 HYDMAP button box.

The button box (Figure A1.19) has seven controls to receive information from the model procedures and to convey user actions to the HYDMAP module procedures. The controls in the button box are listed as follows:

Colour box: The "Colour box" is a type of control called the combo box with a list of colours that the user can select by clicking the arrow on the box. The colour selected is used for the drawing of module routes and other lines on the HYDMAP user interface.

Module Label: The "Module label" receives information from the clicking event on the module icons. The label displays the identification number of the clicked module in the network file when the user clicks on a module icon.

Position button: Clicking the "Position button" will allow the user to be able to change the position of the HYDMAP button box. This is useful in cases where the screen position of the button box may obstruct the network view.

Shape button: Clicking the "Shape button" will change the shape of the button box such that it can be fitted in particular locations on the interface to avoid cluttering the interface.

Saving indicator: The "Saving” indicator is a label that shows the user when module routes are being saved. If the button has a cyan colour without the text "Saving" in it, then the module routes will not be saved. To change the state to allow the saving of the routes the menu button "Draw and save" has to be clicked.

Monthly and Annual graph options: These two option buttons are clicked to select a monthly plot or an annual plot of the time series data of a selected file for the displayed modules.

1.11 HYDRO25 output files

The main output files in the model HYDRO25 have data formatted in the HYDRO25 monthly data format. These files can easily be used by other modules in the catchment system. For example, the flow file from the runoff module can be used as inflow into a reservoir located downstream. The output files are discussed below for each of the HYDRO25 modules.

RES25

The RES25 module generates a total of six output files. Five of these files are overwritten when another RES25 module is run in the same directory. The sixth output file is the file entered in the main user interface inputs as file number four.

The output data in this file are replaced if the user does not specify a different output for subsequent simulations of RUN25. Five of the files use similar names for all the RES25 modules in each network. The five file names are listed in Table A1.7.

Table A1.7 RES25 output files.

Default file name	File contents
SpillsZ.txt	The file will contain data on the monthly volume of water released as spillage, due to the dam being full
IFRZ.txt	The amount of water released to meet "In-stream Flow Requirements" is entered in this file on a monthly basis.
VolumeZ.txt	The volume of water in the storage at the end of each month is entered in this file
ReleaseZ.txt	Amount of water that is released for demands specified as input files 2 and 3 of the main user interface is entered in this file for each RUN25 simulation
BalanceZ.txt	The storage water balance is entered in this file. The file should ideally have zero values for all months if the model is not to end up with "unaccounted for water"
The "**Z**" is the number of the module that will have generated the output and the counting will be applied only to the RES25 modules	

RUN25

The module generates three output files listed as follows:

Output file 1: This file has a name given by the user while building the network file. The file contains the monthly flows generated by the rainfall/runoff simulation. The name of the file is specified in the main user interface under the "Output file" column heading.

Output file 2: The file has the same name as the monthly rainfall file name, except that the extension ".dat" is used. The naming method in "Output file 2" requires that the use of the extension ".dat", be avoided in other modules since such files risk being replaced if the name is the same as that of the rainfall file. "Output file 2" will contain the monthly flows in a format that can be opened to fit in three columns in a spreadsheet programme such as Lotus 1.2.3, Quattro or Excel. This format is suitable for plotting of monthly hydrographs in existing spreadsheet applications.

Output file 3 : The file has a name derived from the input monthly rainfall file name where the text "gr.prn" has been used to replace the file name's extension. This file contains data on the monthly rainfall that have been used as the input in the model. The data are in a format similar to "Output file 2".

CHAN25

The module generates two output files. The first one is the output file that the user will have entered in the main user interface as the output file name. The file contains the result of the channel simulation on a monthly basis. The second file is a water balance file. In this file, the CHAN25 calculations are checked to determine the correctness of the water balance in all months simulated. The water balance output file has the same name as the specified output file with the extension ".bal" replacing the name given by the user.

FACTORFLOW

The module splits flows in terms of fractional proportions that are entered as inputs by the model user. A single file output is produced which will be the result of factoring all monthly flows in the original input file.

FLOWADD

The module generates a single file in the HYDRO25 monthly format. The file name is the same as that specified by the user in the main user interface for the module outputs.

IRRIG25

The irrigation routine generates two files, an irrigation demand file and a return flow file. The irrigation routine should always be run before the water supply source such that the irrigation file generated here is used by the water source such as a dam, channel or addition module to generate a monthly water demand.

1.12 HYDRO25 error handling

Error handlers have been included in the application to avoid situations where the application crashes because an error has occurred. The development of the error handling facility was designed to enable the application to inform the user of the occurrence of such errors and to allow the process to be repeated without having to exit the application. In many cases, some entries that cause errors will not be accepted by input handling procedures that have been included with the application code. While error handlers alone cannot completely assist in correcting problem areas if there is no information on where this error occurred, a system was included to give a guide on identifying the error locations. Table A1.8 shows the labels and numbers used to identify errors in the model.

Table A1.8 Model error location system.

Module	Count letter	User interface error location	RUN button routine error
RAIN25	A	1	-
RUN25	B	2	22
FLOWADD	C	3	33
FACTORFLOW	D	4	44
CHANNEL	E	5	55
RES25	F	6	66
CAL25	J	7	-
DAILYRAIN	-	-	-

In the table, the count letter is used to identify the module within the code. The letter will have the value for the position of the module in the network that will be in current use. In the module parameter input interface, the single digit numbers will appear in the title bar of the error messages for the respective module interface. As an example, the error message boxes will have titles such as "Error at 6.2". The "6" will refer to the RES25 module, and the "2" will refer to a sub-routine in the module RES25.

The running of the network occurs when the "Run" button of the main user interface is clicked. The "Run" button is connected to the code that calls the different modules in the same order as they will be given in the network file, assigns the appropriate parameter files to them, and runs them. If an error occurs in any of the modules then the title bar of the error message will have a number such as 44 for the CHAN25 module. A typical message will read, "Error at: 22.1: 2". The number "22" is to identify the module RUN25 in the "Run" mode, the "1" identifies a sub-routine of the RUN25 module. The "2" that comes after the semicolons is the number that will be carried by the count letter during the running at the moment of the error. The number "2" means that the model had simulated 1 RUN25 module already and that the error has occurred when the second RUN25 module was being simulated. Using the information given by "22.1:2" and the actual error message giving details on what happened when the programme stopped the user can go straight to the inputs for that particular module to correct the source of the error.

An error with "B6" in the title of the message box refers to an error in the "Run" button outside of the modules. The errors in this location will be mostly associated with the network file.

The RAIN25 module is another area where errors may not easily be accounted for. The errors that are difficult to locate are usually encountered after the "Execute" button is clicked. The RAIN25 module can be used to work on up to ten files at a time. When an error occurs which is associated with a file in the Execution code, the title of the message box will show the name of the last file that is currently being processed or has attempted to be processed.

All buttons that are likely to cause errors have error handlers. Most of the errors did not need any system of numbering as they were directly related to what the user will have done just before the error occurs. These errors usually have no connection to other processes that may make them difficult to correct. The user should deal with such errors by revising the step he/she carried out just before they occurred.

1.13 Common user procedures in network modules

The term "network modules" in this study refers to the modules that are run in a particular sequence determined by the network file when the "Run" command of the main user interface is executed. The network file contains information in text format on which module should be run at each stage of the simulation and defines the inputs to associate with the different processes. The parameter input interfaces of the network modules, RUN25, CHAN25, RES25, IRRIG25, FLOWADD and FACTORFLOW perform very similar functions. The common steps in the use of the network module interfaces are discussed in the following section.

1) In the main user interface a “Start” button is used to open a new network file or to create a new file.
2) Editing of the module inputs is possible after enabling the edit mode. To enable the edit mode, the menu command is clicked followed by clicking "Edit routines". The module names which previously could not be clicked, that is they were disabled, can now receive focus when the user clicks on them.
3) An existing routine is selected by clicking in the combo box, a control that allows selection from a list of text items, in this case the text items are the module names. If a new module is to be used it is added by clicking on the “Add” button.
4) A yellow highlighter is used to show the model user which module has the focus. To work on the module that has the focus, the “Edit” button is clicked.
5) The user interface for the selected module interface will pop up without opening the associated data files, which are referred to as the parameter files in this model.

In the module interfaces, the following steps apply to all parameter input interfaces.

a) To open an existing parameter file, the “Open” button is clicked while the user is in the edit mode for the module to be edited. In each parameter input interface there are two file filter options in the “Open file” dialogue boxes for the user to either select a file with a default extension for the particular parameter file, or to choose from all files. For example RUN25 parameter files should have the extension “.001”. Different file name extensions have been specified for the different parameter files to allow easier referencing and to avoid the use of wrong inputs in the model in cases where the user may be running large models with many input files. The model user is advised to enter the file name only, without the extension, when saving parameter files. The model adds the appropriate extensions.
b) Saving a parameter file is achieved through the use of the buttons “Save As” or “Save”. When the module inputs have been edited the "Save As" button has to be

used. This button allows the user to specify a new file name if he/she wishes. The "Save" button is a quick way of saving the inputs without changing the file name.

c) The “View” button or “Enter Key” is used to view the position of the routine in the water resources network.

d) The "New" button is used to clear module inputs. Only inputs that will be tedious to clear individually have been connected to the "New" button.

e) A "Back" button returns the model user to the previous screen. The same can be achieved using the "Escape" key or clicking the flower icon on the right hand top corner of each parameter-input form.

f) The buttons with the caption "Add" and "Develop" will place more form controls at run time. The controls added to the form in this manner are also referred to in this model as dynamic controls. The user will be able to enter time series data in the dynamic controls. The button with the caption "Remove" will remove the last added dynamic control. The "Add", "Develop" and "Remove" buttons apply to the parameter input forms for FACTORFLOW, RES25 and RUN25.

Appendix A2: The Doring River case study: Data collection, analysis and entry

2.1 Data collection

2.1.1 Introduction

Water resources studies that utilise models mainly rely on time series data and the mathematical formulations in the model. In the simulation of the Doring River catchment, historical time series data were used in the model HYDRO25. It was assumed that for the period considered in the simulation of proposed catchment developments, the rainfall and evaporation patterns would have the same trends as those recorded since 1925.

Several studies on climatic changes have indicated that there is a continuous increase in the concentration of carbon dioxide in the atmosphere creating a "Greenhouse" effect that is responsible for increases in atmospheric temperature, a condition commonly referred to as "Global warming". Atmospheric changes have also been identified to be leading to a series of other climatic changes that differ for different areas (Pittock, 1990; Schulze and Perks, 2000; McCarthy, Canziani, Leary, Dokken, and White, 2001). The other climatic changes include increases in annual precipitation in high and mid latitudes and most equatorial regions, while general decreases in precipitation are believed to be taking place in the sub-tropics of both hemispheres.

Studies in southern Africa using climatic models (Arnell, 1999) have shown that annual precipitation is likely to decrease by at least 10 % and potential evaporation will increase by between 4 and 10 % over the next 100 years due to global warming. On the other hand, increased concentration of carbon dioxide will increase the water use efficiency of plants and stimulate nitrogen fixation (McCarthy *et al.*, 2001). There are considerable uncertainties in trying to predict the magnitude of any effects of global warming, and more particularly, the related regional and local effects on rainfall such that more research is needed to narrow down the uncertainties (Pittock, 1990). In this study it is noted that climatic changes have an impact on the correctness of water resources simulation results. However, due to the uncertainties surrounding attaching measurable quantities to these effects, an assumption has been made that, for the period projected in the irrigation development proposals, that is the 74 years used in Section 9, the impact of such climatic changes on water availability assessment parameters used in the case studies of this research will be minimal.

The study used time series data stretching from 1925 to 1999 to assess the historical catchment development and to simulate the proposed developments. Section 3.3 covers the general background to the data used in the HYDRO25 modelling case study. In this section the collection and analysis of data used in the Doring River catchment analysis are discussed.

2.1.2 Rainfall data

The rainfall data used in the model came from different sources due to a number of technicalities. The following organisations were approached to provide data and made some data available for this study.

(a) The Computing Centre for Water Research (CCWR)
(b) The Weather Bureau
(c) The Department of Water Affairs and Forestry: Hydrology Directorate

The Hydrology Directorate in DWAF, which has its own rainfall stations in the catchment area, had the most up to date daily records of data. The CCWR had monthly data for a number of the stations, though these data were noted to be shorter than the simulation period with most station records ending in the 1980s and early 1990s. The Weather Bureau was noted to have closed a number of its rainfall gauges such that the study had to rely on data from a few stations, in spite of several stations having been identified as being in the area. The data came in different formats and had to be processed into the HRU format that is used by the patching programme "patchr" where filling of missing and unreliable records was done. The following rain gauges were used in the patching process 42227, 42532, 42669, 66027, 45184, 44286 and 44050 to generate two patched rainfall files for the two sub-catchments, KBV and Aspoort sub-catchment. The catchment divisions are shown in Figure 9.2 with positions of rainfall stations in the study area.

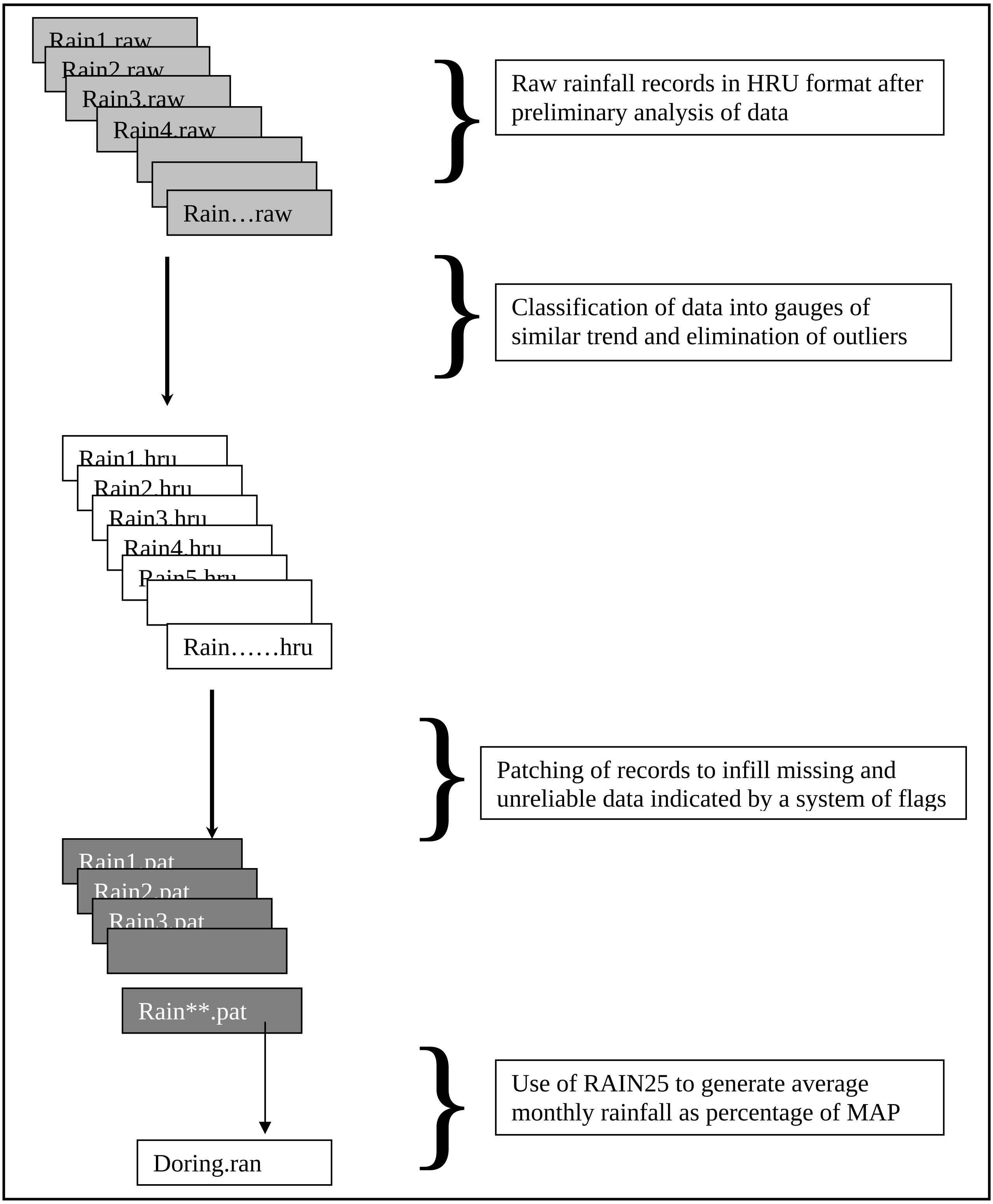


Figure A2.1 Processing of rainfall data.

The model uses monthly rainfall data expressed as a percentage of mean annual precipitation (MAP). The values of MAP were obtained from the WR90 reports (Midgely *et al.*, 1994). Figure A2.1 shows the general process followed to obtain the average monthly rainfall files used in the model.

The module RAIN25 referred to in Figure A2.1 was used to obtain the rainfall files used in the model. In the module RAIN25 a number of rainfall gauge data files (a maximum of ten files) are entered by selecting their names using the module RAIN25's selection list. The file data will be of the "patched" HRU type data (Pegram, 1994) with rainfall data in tenths of millimetres, a method used to exclude the decimal point in the programme "patchr". Three sets of such data for a short period are shown in Figure A2.2 for the stations 42227, 66027 and 42669.

Rain25 Output

```
                        AVERAGE RAINFALL IN PERCENTAGES FOR THE CATCHMENT: HYDRO
                                    DETAILS OF RAINFALL STATIONS USED
                             DATA SOURCE                 PERIOD OF RECORD
                             042227                        1920 TO 1999
                             042669                        1945 TO 1999
                             066027                        1917 TO 1999
                                    RAINFALL INPUT AS PERCENT M.A.P.
Yea  No. of  Oct    Nov    Dec    Jan    Feb    Mar    Apr    May    Jun    Jul    Aug    Sep    Year
     Gauges
-----------------------------------------------------------------------------------------------------
1960  3            1.21   8.58   4.23   0.71   3.86  12.00  14.61  12.39  11.70  10.40  17.23   99.06
1961  3     1.09   0.00   0.00   2.35   2.39   5.30   7.06   5.03  40.18  11.00  28.23   4.35  106.98
1962  3    18.69   5.07   0.25   3.78   1.16   1.00   2.80   3.25  14.22  15.24  31.49   2.85   99.80
1963  3     3.10   8.18   9.71   0.05   1.73   2.70   2.85   5.45  23.84   8.94  14.31  10.26   91.12
```

Gauge 1

```
OUTPUT FROM THE INFILLING/EXTENSION PROGRAM – PATCHR
 THE CONTENTS OF THE FILE 042669.PAT
--------------------------------------------------------------------------------
 042669    1945 1999   3678.
042669   1960        60  235  115   20   85  377  195  505  255  255  710   2837
042669   1961    0    0    0    0    0   75  170  255 1090  230  775  130   2725
042669   1962  620  215    0  255    0    0    0  134  505  530 1265  100   3624
042669   1963  190  150  515    0    0    0  139+ 182  680  355  345  327   2883+
```

Gauge 2

```
 OUTPUT FROM THE INFILLING/EXTENSION PROGRAM – PATCHR
 THE CONTENTS OF THE FILE 042227.PAT
--------------------------------------------------------------------------------
 042227    1920 1999   4726.
042227   1960        95  135  200   25  102  250  375  360  550  665  875   3802
042227   1961  155    0    0  100  238  655  470  385 1935  760 1355  240   6293
042227   1962 1125  350   35@  20    0   75   28   70  762  766 1637  150   5018@
042227   1963  145  505  270    7  161  130  150  475  885  710 1085  405   4928
```

Gauge 3

```
 OUTPUT FROM THE INFILLING/EXTENSION PROGRAM – PATCHR
 THE CONTENTS OF THE FILE 066027.PAT
--------------------------------------------------------------------------------
 066027    1917 1992   2812.
066027   1960         0  464  150   30  200  575  860  445  465  287  390   3926
066027   1961    0    0    0  139   60    0  186    0 1405  300  983  125   3198
066027   1962  433   55    0  112   98   40  220  130  360  425  715   75   2663
066027   1963   30  275  265    0   50  150   45   38  965   60  298  375   2551
```

Figure A2.2 Example of patched input data and a section of RAIN25 output.

Figure A2.2 shows an example of the inputs to the RAIN25 module and the rainfall data produced by the model as a percentage of the MAP. The calculation of the rainfall values in RAIN25 uses Equation A2.1, below:

$$R = \sum_{1}^{n} \left(\frac{R_i}{MAP_i}\right) \times \left(\frac{100}{n}\right) \quad \text{……………………………………………….Equation A2.1}$$

Where

R = Rainfall for a single month for the area expressed as a percentage of MAP for the catchment (mm)

R_i = Rainfall for a single month from station "*i*" patched data expressed in tenths of millimetres (mm)

MAP_i = Mean annual precipitation of station "*i"* (mm)

n = Number of gauges with reliable rainfall data in that month (The user can specify to include flagged unreliable data or to exclude them in the input options of RAIN25)

In the example illustrated in Figure A2.2 for three rainfall gauges, Equation A2.1 is used in RAIN25 as shown in Equation A2.2 for each of the months. In the data shown in Figure A2.2, two months have patched data indicated by the flags "+" and "@". The months with patched data are April 1963 for gauge 1 and December 1962 for gauge 2. In months with flagged data the model user has a choice to include or exclude them from the calculation of the percentage rainfall. When the patched values in Figure A2.2 are excluded, Equation A2.1 will use n = 2 and values from two gauges for the concerned months only. Equation A2.2 shows the rainfall calculation for three data sets.

$$R = \left(\left(\frac{R_1}{MAP_1}\right) + \left(\frac{R_2}{MAP_2}\right) + \left(\frac{R_3}{MAP_3}\right)\right) \times \frac{100}{3} \quad \text{……………………………….Equation A2.2}$$

To get the value of 2.14 % in October of 1960 shown highlighted in the top section of Figure A2.2 with the heading "RAIN25 Output", the variables in Equation A2.2 had the following values:

R_1 = 25; R_2 = 170 and R_3 = 60, the three being the October 1960 values from each of the gauges highlighted in Figure A2.2 in units of tenths of millimetres. MAP_1 = 3678, MAP_2 = 4726 and MAP_3 = 2812, these being the mean annual precipitation for each of the three rainfall stations for the whole record length being used by RAIN25 in units of tenths of millimetres. When the model runs using the rainfall file in percentage of MAP, the percentage values are multiplied by the MAP of the catchment to determine the rainfall depth for the area. The MAP for a catchment is obtained by calculating the mean of annual rainfall for long series of data from several stations or from isohytal maps of the area. The RAIN25 module has functions to calculate the long-term mean annual rainfall for up to ten rainfall stations using monthly rainfall as inputs.

2.1.3 Evaporation data

In the model long-term average evaporation data for the Doring River catchment were used. The choice to use long-term average evaporation was based on previous studies and earlier work in the model, HYDRO25, where it was noted that the evaporation inputs entered in a similar method as rainfall data, that is using actual monthly records, did not produce significant improvements to the model results. Previous work by Pitman (1973), BKS (1986), Pitman and Kakebeeke (1993) and DWAF (2000) in the simulation of catchments used mean monthly evaporation as inputs in the water resources models they developed. The monthly evaporation data were obtained from the Weather Bureau as well as DWAF's hydrological directorate. The model used average monthly Symon's pan evaporation for the calculation of the water losses from the reservoirs and other open surfaces. The calculation of the amount of water required to irrigate crops after losing water through evapotranspiration was done using A-pan evaporation data. The choice to use the A-pan in the irrigation modules and Symon's pan evaporation in open water losses was based on the requirement to use evaporation figures which are related to crop evaporation, while on the other hand the hydrological viewpoint was to use evaporation that is meaningful in describing evaporative losses from open water bodies such as reservoirs. Kunz and Schulze (1995) and Green (1985) point out that A-pan evaporation is more meaningful in describing evapotranspiration while other methods, including Symon's pan evaporation, are suggested for open water evaporation simulations. The evaporation data supplied by the Weather bureau were for gauges located at different points in the catchment. To calculate the long-term average Symon's pan evaporation for the entire catchment, the mean annual evaporation of the catchment was estimated on the basis of records from a number of gauges and available information on the average annual evaporation of the catchment using literature such as the report by Green (1985). The average monthly evaporation for the sub-catchment areas considered in the study were determined by calculating the mean monthly evaporation at each gauge as a percentage of the respective mean annual evaporation rates. The percentages for each month from the different gauges were averaged to obtain the monthly distribution of the mean annual catchment evaporation which is shown for the two sub-catchments in Table A2.1 and Table A2.2 below.

Table A2.1 KBV sub-catchment monthly distribution of evaporation expressed as a percentage of the catchment's annual evaporation.

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
8.9	12.1	14.5	16.4	11.9	10.7	6.3	3.9	2.8	3.1	3.9	5.5

Table A2.2 Aspoort sub-catchment monthly distribution of evaporation expressed as a percentage of the catchment's annual evaporation.

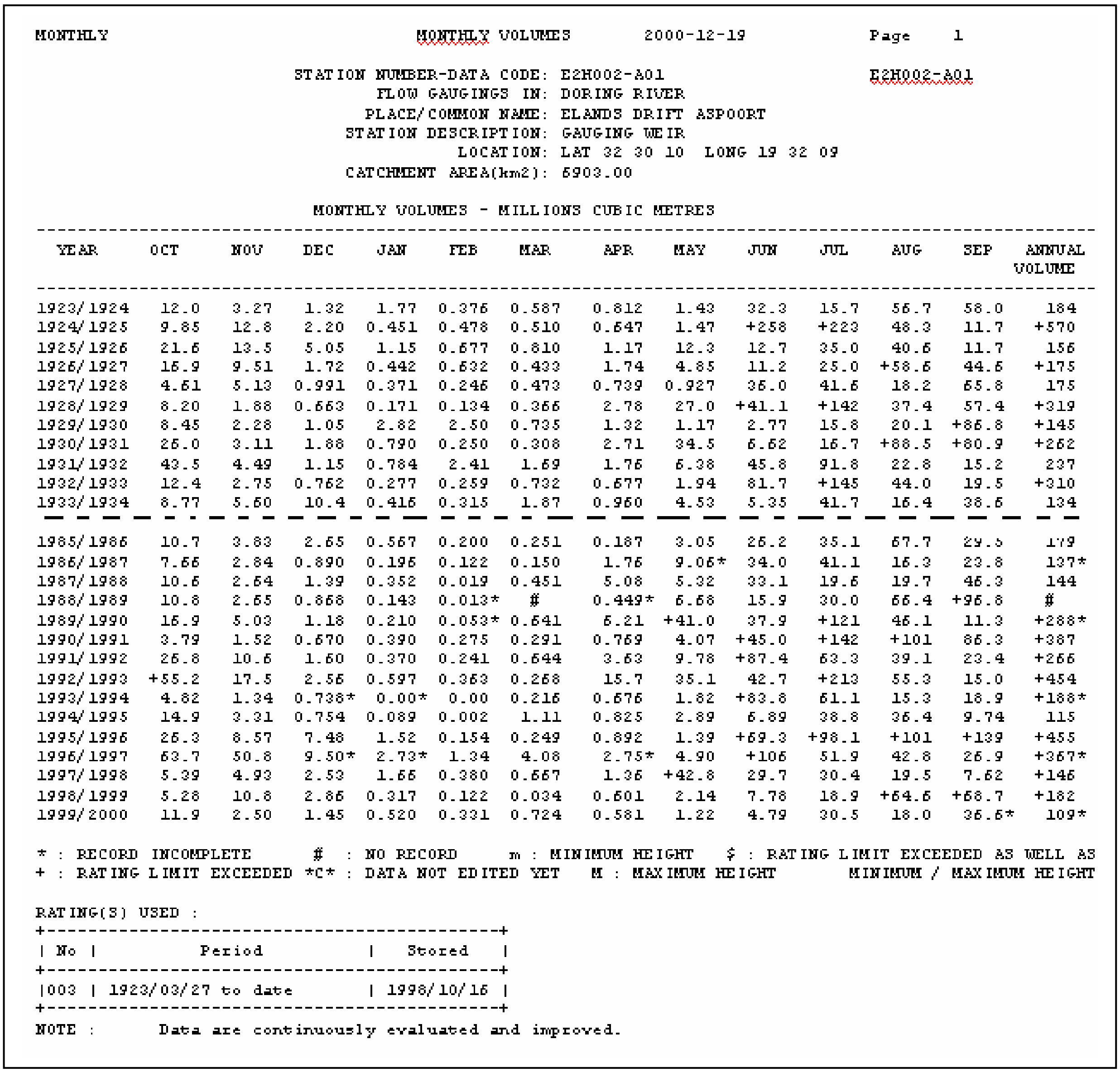
Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep
9.1	12.0	14.2	15.5	12.1	10.5	6.7	4.2	2.8	3.1	4.0	5.8

2.1.4 Land use data

Land use data were entered in the model as a time series input to account for the process of development that occurs over time. The land use inputs were mainly for irrigation developments. Data on existing irrigation were obtained from a report on the Olifants-Doring system (Theron and du Plessis, 1998). Changes in the catchment's paved areas, (*i.e.* are built up areas and roads which are treated as impervious areas), were estimated on the basis of development trends recorded by Midgeley *et al.*, (1994). These changes in the areas of impervious surfaces have a large impact on the catchment runoff and were included as a time series based catchment development event.

2.1.5 Streamflow data

The model HYDRO25 uses existing records of runoff to calibrate the amount of water flowing in the catchment. DWAF's gauge E2H002 is located on the Doring River at latitude 32° 32' 10" and longitude 19° 32' 09", which is the same location as the proposed Aspoort Dam lying at the downstream end of the study area. This gauge had some missing records in certain months but the data were the best available for this study. Patching of the missing records was done for gauge E2H002 on the daily flow records using a specialised application developed for the patching of Clanwilliam Dam inflows in a study in the same hydrological region as the Doring River (Dube, 2000). Another runoff gauge located further downstream, gauge E2H003, was used as additional input in the patching programme. The most up to date records for gauges E2H002 and E2H003 were obtained from DWAF in daily flow format and had to be processed to generate the monthly records used in the calibration of the model. Apart from missing records, the data had a number of other shortcomings that had to be overcome, for example, suspect values that were not flagged and minimum records that could not be relied on. General data observations as well as statistical and arithmetic calculations directed at determining the trends in the records and excluding outliers were performed on the data before patching could be done. Figure A2.3 shows a typical monthly record of flows as it was when it was supplied by the Hydrology Directorate of DWAF.



```
MONTHLY                              MONTHLY VOLUMES       2000-12-19            Page    1

                         STATION NUMBER-DATA CODE: E2H002-A01                    E2H002-A01
                                FLOW GAUGINGS  IN: DORING RIVER
                               PLACE/COMMON NAME: ELANDS DRIFT ASPOORT
                             STATION DESCRIPTION: GAUGING WEIR
                                        LOCATION: LAT 32 30 10  LONG 19 32 09
                             CATCHMENT AREA(km2): 6903.00

                          MONTHLY VOLUMES - MILLIONS CUBIC METRES
-----------------------------------------------------------------------------------------------
  YEAR      OCT     NOV     DEC     JAN     FEB     MAR      APR     MAY     JUN     JUL     AUG     SEP    ANNUAL
                                                                                                           VOLUME
-----------------------------------------------------------------------------------------------
1923/1924   12.0    3.27    1.32    1.77  0.376   0.587    0.812    1.43    32.3    15.7    56.7    58.0     184
1924/1925   9.85    12.8    2.20   0.451  0.478   0.510    0.647    1.47    +258    +223    48.3    11.7    +570
1925/1926   21.6    13.5    5.05    1.15  0.677   0.810     1.17    12.3    12.7    35.0    40.6    11.7     156
1926/1927   16.9    9.51    1.72   0.442  0.632   0.433     1.74    4.85    11.2    25.0   +58.6    44.6    +175
1927/1928   4.61    5.13   0.991   0.371  0.246   0.473    0.739   0.927    36.0    41.6    18.2    65.8     175
1928/1929   8.20    1.88   0.663   0.171  0.134   0.366     2.78    27.0   +41.1    +142    37.4    57.4    +319
1929/1930   8.45    2.28    1.05    2.82   2.50   0.735     1.32    1.17    2.77    15.8    20.1   +86.8    +145
1930/1931   26.0    3.11    1.88   0.790  0.250   0.308     2.71    34.5    6.62    16.7   +88.5   +80.9    +262
1931/1932   43.5    4.49    1.15   0.784   2.41    1.69     1.76    6.38    45.8    91.8    22.8    15.2     237
1932/1933   12.4    2.75   0.762   0.277  0.259   0.732    0.677    1.94    81.7    +145    44.0    19.5    +310
1933/1934   6.77    5.60    10.4   0.416  0.315    1.87    0.960    4.53    5.35    41.7    16.4    36.6     134
 — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — — 
1985/1986   10.7    3.83    2.65   0.567  0.200   0.251    0.187    3.05    26.2    35.1    67.7    29.5     179
1986/1987   7.66    2.84   0.890   0.196  0.122   0.150     1.76   9.06*    34.0    41.1    16.3    23.8    137*
1987/1988   10.6    2.64    1.39   0.352  0.019   0.451     5.08    5.32    33.1    19.6    19.7    46.3     144
1988/1989   10.8    2.65   0.868   0.143  0.013*    #     0.449*    6.68    15.9    30.0    66.4   +96.8      #
1989/1990   16.9    5.03    1.18   0.210  0.053*  0.641     6.21   +41.0    37.9    +121    46.1    11.3   +288*
1990/1991   3.79    1.52   0.670   0.390  0.275   0.291    0.769    4.07   +45.0    +142    +101    86.3    +387
1991/1992   26.8    10.6    1.60   0.370  0.241   0.644     3.63    9.78   +87.4    63.3    39.1    23.4    +266
1992/1993  +55.2    17.5    2.56   0.597  0.363   0.268     15.7    35.1    42.7    +213    55.3    15.0    +454
1993/1994   4.82    1.34   0.738*  0.00*   0.00   0.216    0.676    1.82   +83.8    61.1    15.3    18.9   +188*
1994/1995   14.9    3.31   0.754   0.089  0.002    1.11    0.825    2.89    6.89    38.8    36.4    9.74     115
1995/1996   26.3    8.57    7.48    1.52  0.154   0.249    0.892    1.39   +69.3   +98.1    +101    +139    +455
1996/1997   63.7    50.8   9.50*   2.73*   1.34    4.08    2.75*    4.90    +106    51.9    42.8    26.9   +367*
1997/1998   5.39    4.93    2.53    1.66  0.380   0.667     1.36   +42.8    29.7    30.4    19.5    7.62    +146
1998/1999   5.28    10.8    2.86   0.317  0.122   0.034    0.601    2.14    7.78    18.9   +64.6   +68.7    +182
1999/2000   11.9    2.50    1.45   0.520  0.331   0.724    0.581    1.22    4.79    30.5    18.0   36.6*    109*

* : RECORD INCOMPLETE       #  : NO RECORD       m : MINIMUM HEIGHT    $ : RATING LIMIT EXCEEDED AS WELL AS
+ : RATING LIMIT EXCEEDED *C* : DATA NOT EDITED YET    M : MAXIMUM HEIGHT        MINIMUM / MAXIMUM HEIGHT

RATING(S) USED :
+----------------------------------------------+
| No |             Period           |  Stored  |
+----------------------------------------------+
|003 | 1923/03/27 to date           | 1998/10/16 |
+----------------------------------------------+
NOTE :       Data are continuously evaluated and improved.
```

Figure A2.3 Original version of monthly flow records from the gauge E2H0002 as supplied by DWAF.

2.1.6 Data analysis and patching

Data collection involved searching for all the catchment data that could be used in the model without setting any preference to any one source of data. In the case of rainfall data, records from other rain gauges close to the catchment area were also considered since the record to be used in the model had to represent average rainfall for a large area. Feedback for rainfall data requests from the different institutions reduced the number of possible stations to around twenty gauges. The vast amounts of data required in the

HYDRO25 model are mainly monthly rainfall type of data, such that the data analysis stage focussed on the analysis of rainfall data. The data assessments started with simple observation where a number of stations were excluded after showing major shortcomings when the following considerations were made:

(a) Inadequate record length
(b) Too many zero values or unflagged suspicious values
(c) Presence of negative values in the records
(d) Chronological order not being followed in the records
(e) Too many flags generating suspicion on many records. In some cases some records from the CCWR had flags for all the values for a rain gauge
(f) Records from different data sources with the same rainfall gauge numbers but completely different values

Further data analysis involved the use of mathematical and graphical methods. Mass plots were done to check on data consistency. A typical double mass curve of the rainfall gauges 042669 and gauge 086079 is shown in Figure A2.4.

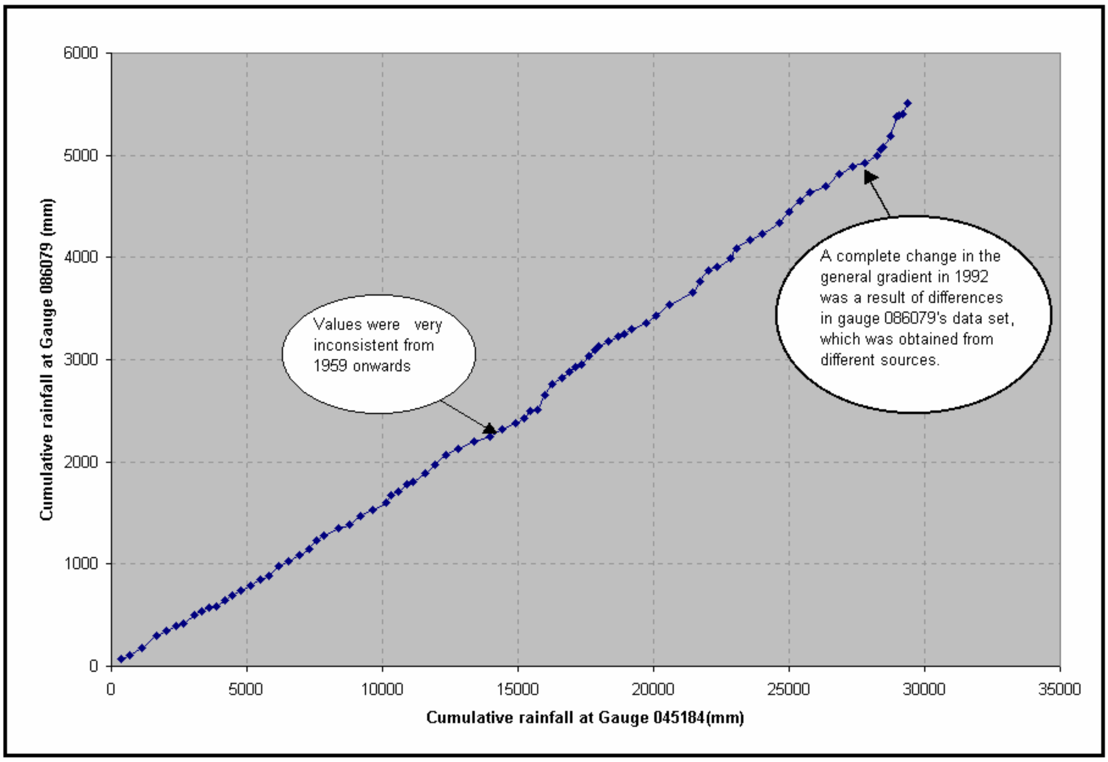


Figure A2.4 Double mass curve of rainfall gauges 042669 and 086079 for the period 1917 to 1999.

The double mass curve of gauge 086079 and 042669, shown in Figure A2.4, gave a number of inconsistencies, some of which are indicated in the figure. Plots of data from the two stations, 086079 and 042669 against that from the other stations in the catchment indicated that gauge 086079 had a number of shortcomings that made it unsuitable for use in the simulation.

Geographical plotting of mean annual precipitation to identify any unusual patterns as well as split sample testing of means and variances were also part of the pre-treatment stage for the data. The software application, Classr (Pegram, 1994) was then used to classify rainfall gauges into groups with a similar trend and for further identification of outliers. The application Classr used a measure of distance to identify gauges of similar nature. The distances or physical locations of the rainfall stations are derived from the naming convention used for rain gauges. In the application statistical calculations were used to identify outliers. Two sets of rainfall data were obtained for the two sub-catchments, the Koue Bookkeveld and the Aspoort sub-catchment. The two sets of data were used in the patching programme to fill in missing or unreliable records. The unreliable records had flags/indicators added at the data source and additional flags placed by the Classr application.

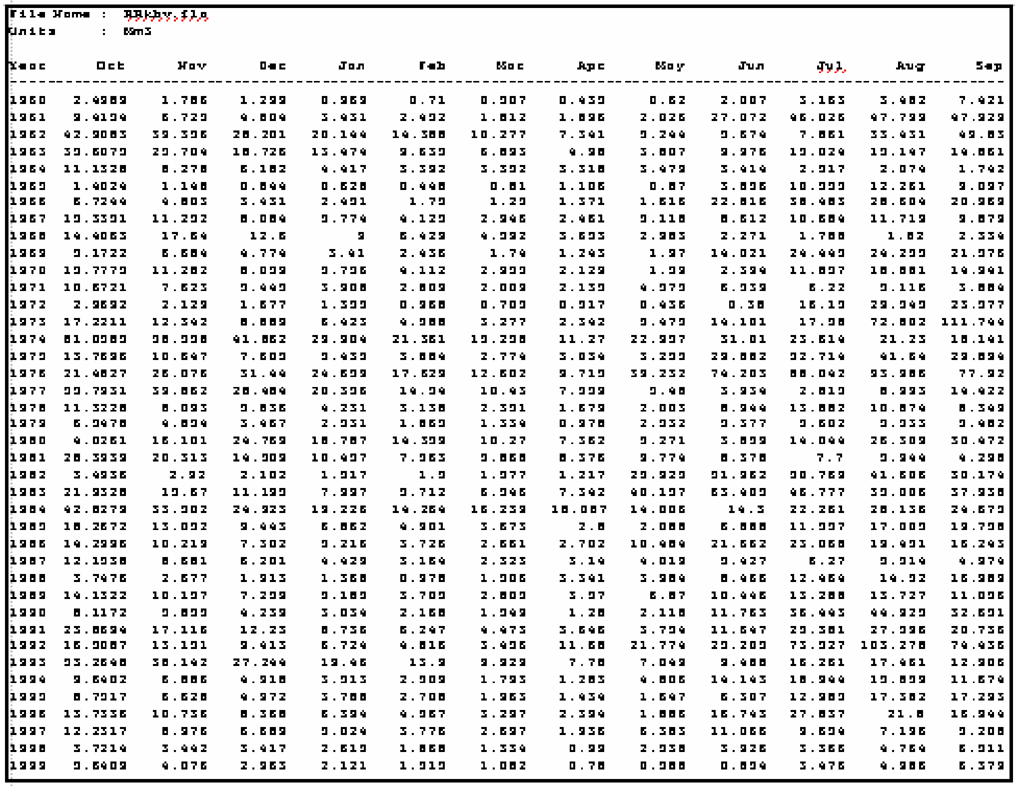
The grouped and flagged rainfall records were patched using the application Patchr (Pegram, 1994). The patching programme used stepwise multi-linear regression based on the EM algorithm. In the EM algorithm, the idea is to recursively substitute regressed data for those that are missing and then re-estimate the regression (Makhuvha, 1988). The EM algorithm has the advantage that the other records that are used to patch the unreliable gauge data can have missing data, a feature which is not possible when the general multi-linear regression method is used. In multi-linear regression the records used to patch another data set must not have missing or unreliable values; such data sets are very rare to find.

2.1.7 Data input formats in HYDRO25 and the output files

The model, HYDRO25 relies on data stored in a system of files to pass information from the user to the model, and from one model module to another. Calculations in the model rely on values entered in files as inputs. The hydrological data are mainly on a monthly basis. A daily rainfall input for at least one year is needed to determine the best daily rainfall distribution in the model. The actual values in the daily data file are not used by the model. The model uses this input to determine how to distribute a monthly value of rainfall. The other input files are the parameter files with information on what the model should do for each of the component modules. A network file is the first input to building any system, and has details about all the modules and a list of the data files to be used by each module, and the directory locations of where each processing stage should save information for subsequent stages to access in the simulation process.

2.1.7.1 The HYDRO25 monthly data format

Figure A2.5 shows the HYDRO25 monthly data format. The first five lines must contain a description of the file name and the headings for each month. The spacing between columns is not critical.



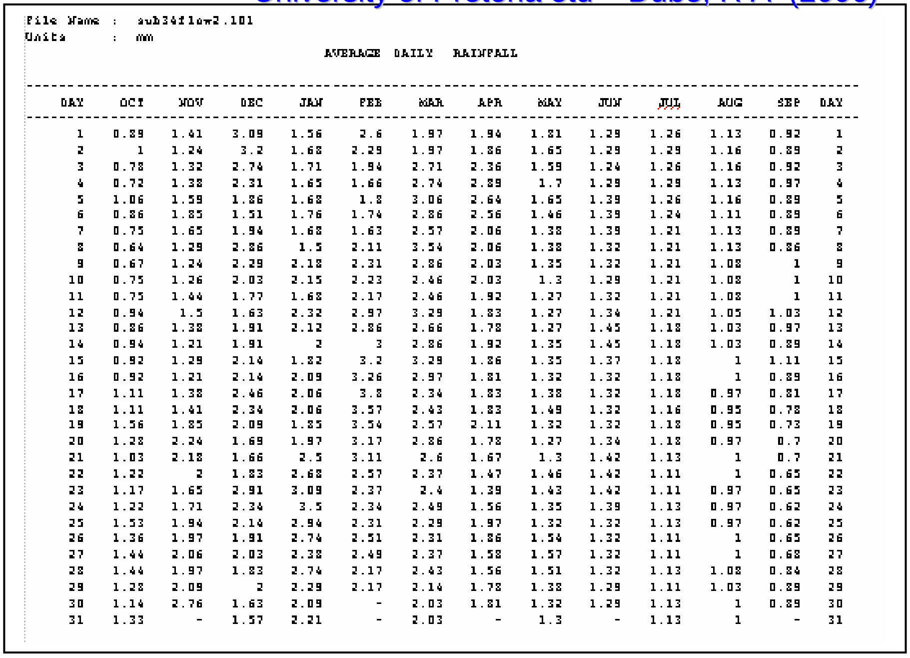
```
File Name :  RRkbv.flo
Units     :  Mm3

Year      Oct      Nov      Dec      Jan      Feb      Mar      Apr      May      Jun      Jul      Aug      Sep
------------------------------------------------------------------------------------------------------------------
1960   2.4989    1.786    1.299    0.969     0.71    0.507    0.455     0.62    2.007    3.163    3.482    7.421
1961   9.4154    6.725    4.804    3.431    2.492    1.812    1.896    2.026   27.072   46.026   47.799   47.929
1962  42.9083   39.356   28.201   20.144   14.388   10.277    7.341    5.244    5.674    7.861   33.431    49.83
1963  35.6075   25.704   18.726   13.474    9.635    6.893     4.98    3.807    9.976   15.024   15.147   14.861
1964  11.1328    8.278    6.182    4.417    3.392    3.392    3.318    3.479    3.414    2.517    2.074    1.742
1965   1.4024    1.148    0.844    0.628    0.448     0.81    1.106     0.87    3.896   10.555   12.261    9.097
1966   6.7244    4.803    3.431    2.451     1.75     1.25    1.371    1.616   22.816   38.483   28.604   20.969
1967  15.3351   11.252    8.084    5.774    4.125    2.946    2.461    5.118    8.612   10.684   11.719    9.879
1968  14.4063    17.64     12.6        9    6.429    4.992    3.653    2.983    2.271    1.788     1.82    2.334
1969   5.1722    6.684    4.774     3.41    2.436     1.74    1.243     1.97   14.021   24.445   24.255   21.576
1970  15.7775   11.282    8.055    5.796    4.112    2.955    2.129     1.59    2.354   11.857   18.881   14.941
1971  10.6721    7.623    5.445    3.908    2.809    2.009    2.135    4.575    6.535     6.22    5.116    3.884
1972   2.9692    2.129    1.677    1.355    0.968    0.705    0.517    0.436     0.38    16.15   29.545   23.577
1973  17.2211   12.342    8.889    6.423    4.988    3.277    2.342    5.475   14.101    17.98   72.802  111.744
1974  81.0585   58.558   41.862   29.904   21.361   15.258    11.27   22.997    31.01   23.614    21.23   18.141
1975  13.7696   10.647    7.605    5.455    3.884    2.774    3.034    3.255   29.882   52.714    41.64   29.894
1976  21.4827   26.076    31.44   24.659   17.629   12.602    9.715   59.232   74.203   88.042   93.986    77.92
1977  55.7931   39.862   28.404   20.356    14.54    10.43    7.559     5.48    3.934    2.815    8.993   14.422
1978  11.3228    8.093    5.836    4.231    3.138    2.351    1.679    2.003    8.944   13.882   10.874    8.349
1979   6.5478    4.854    3.467    2.531    1.865    1.334    0.978    2.932    5.377    5.602    5.533    5.482
1980   4.0261   16.101   24.769   18.787   14.359    10.27    7.362    5.271    3.859   14.044   26.309   30.472
1981  28.3939   20.313   14.509   10.457    7.563    5.868    8.376    9.774    8.378      7.7    5.944    4.298
1982   3.4936     2.92    2.102    1.517      1.5    1.577    1.217   25.925   51.962   50.769   41.606   30.174
1983  21.9328    15.67   11.155    7.997    5.712    6.946    7.342   40.157   63.405   46.777   35.006   37.938
1984  42.8279   33.502   24.923   15.226   14.264   16.239   18.087   14.006     14.3   22.261   28.136   24.675
1985  18.2672   13.052    9.443    6.862    4.901    3.673      2.8    2.088    6.888   11.557   17.005   19.798
1986  14.2996   10.219    7.302    5.216    3.726    2.661    2.702   10.484   21.662   23.068   19.451   16.243
1987  12.1938    8.681    6.201    4.429    3.164    2.323     3.14    4.019    5.427     6.27    5.514    4.974
1988   3.7476    2.677    1.913    1.368    0.978    1.506    3.341    3.984    8.466   12.464    14.52   16.989
1989  14.1322   10.157    7.299    5.185    3.705    2.805     3.57     6.87   10.446   13.288   13.727   11.096
1990   8.1172    5.855    4.239    3.034    2.168    1.549     1.28    2.118   11.763   36.443   44.925   32.651
1991  23.8694   17.116    12.23    8.736    6.247    4.473    3.646    3.754   11.647   25.381   27.556   20.736
1992  16.9087   13.151    9.413    6.724    4.816    3.496    11.68   21.774   25.205   73.527  103.278   74.436
1993  53.2648   38.142   27.244    15.46     13.5    9.929     7.78    7.049    9.488   16.261   17.461   12.506
1994   9.6402    6.886    4.918    3.513    2.505    1.793    1.283    4.806   14.143   18.944   15.855   11.674
1995   8.7517    6.628    4.972    3.788    2.708    1.963    1.434    1.647    6.307   12.985   17.382   17.293
1996  13.7336   10.736    8.368    6.394    4.967    3.297    2.394    1.886   16.743   27.837     21.8   16.944
1997  12.2317    8.976    6.689    5.024    3.776    2.697    1.936    6.383   11.066    5.654    7.196    5.208
1998   3.7214    3.442    3.417    2.615    1.868    1.334     0.99    2.938    3.926    3.366    4.764    6.511
1999   5.6405    4.076    2.963    2.121    1.515    1.082     0.78    0.588    0.854    3.476    4.986    6.379
```

Figure A2.5 HYDRO25 monthly data format.

The model reads the data in free format, such that the monthly values must be separated by at least a single space. The data do not necessarily have to be in a set of neat columns, though this is important for clear presentation and to identify problems if they do arise while accessing the file. The file has to be created using a simple text editor, such as Notepad or Textpad. The editing of the input data files should avoid the use of specialised word applications such as MS Word or Word perfect. These applications are based on the rich-text software control, which adds formatting to text files and causes access problems when the free format method of reading values is used. How a data file ends is a very important aspect in the HYDRO25 model. There should be no open space at the end of the last data entry. The end of file should be exactly at the last figure typed in the file. The error message "Input past end of file" will be displayed if a file does not end as described. This error results from the computer reading an empty space and attempting to identify that space as a possible input to the model. It will be noted that the same error message is displayed for data read in free format if the data are being distributed to defined variables and it happens that some of the variables expecting to get data assigned to them from a single line fail to get data. An example of such a problem will be encountered if a parameter file is incorrectly altered or if a parameter file from another module is opened in the wrong parameter input interface. In cases such as these, the file end will not be the problem, instead the data format will be the source of the error.

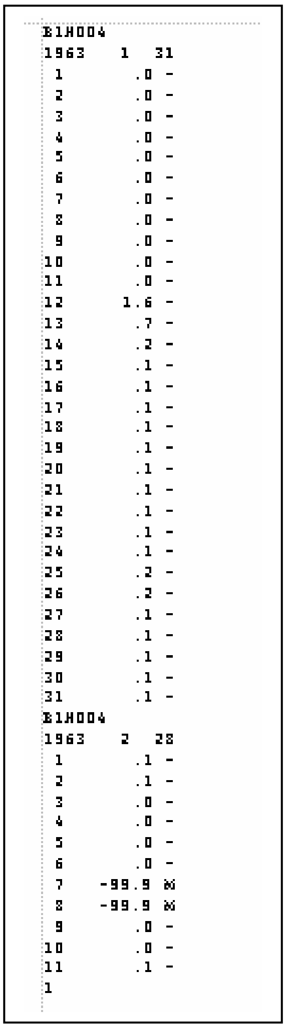
2.1.7.2 HYDRO25 daily data format

The daily data format, if it is available, is used in the RUN25 module. The daily data in this module are rainfall data that are used to distribute the values for monthly flows, interception, evaporation and water seepage into daily components. If the daily data file is not supplied, a default distribution pattern is used that is applied for all the months, and all the years. The distribution pattern obtained from the daily inputs is not varied over the years. The daily rainfall file is obtained using the Daily-Rain module that is accessed by clicking the "Data" button in the main user interface and then selecting the second choice in the selection form that appears. The module uses data in the ACRU (Dent *et al.*, 1995) single data format to generate data in a format that can be used in this model. Figures A2.6 and A2.7 show the HYDRO25 daily data format and the ACRU single format, respectively.



```
File Name :  sub34flow2.101
Units     :  mm
                                          AVERAGE  DAILY  RAINFALL

-------------------------------------------------------------------------------------------------------
   DAY     OCT     NOV     DEC     JAN     FEB     MAR     APR     MAY     JUN     JUL     AUG     SEP   DAY
-------------------------------------------------------------------------------------------------------
     1    0.89    1.41    3.09    1.56     2.6    1.97    1.94    1.81    1.29    1.26    1.13    0.92     1
     2       1    1.24     3.2    1.68    2.29    1.97    1.86    1.65    1.29    1.29    1.16    0.89     2
     3    0.78    1.32    2.74    1.71    1.94    2.71    2.36    1.59    1.24    1.26    1.16    0.92     3
     4    0.72    1.38    2.31    1.65    1.66    2.74    2.89     1.7    1.29    1.29    1.13    0.97     4
     5    1.06    1.59    1.86    1.68     1.8    3.06    2.64    1.65    1.39    1.26    1.16    0.89     5
     6    0.86    1.85    1.51    1.76    1.74    2.86    2.56    1.46    1.39    1.24    1.11    0.89     6
     7    0.75    1.65    1.94    1.68    1.63    2.57    2.06    1.38    1.39    1.21    1.13    0.89     7
     8    0.64    1.29    2.86     1.5    2.11    3.54    2.06    1.38    1.32    1.21    1.13    0.86     8
     9    0.67    1.24    2.29    2.18    2.31    2.86    2.03    1.35    1.32    1.21    1.08       1     9
    10    0.75    1.26    2.03    2.15    2.23    2.46    2.03     1.3    1.29    1.21    1.08       1    10
    11    0.75    1.44    1.77    1.68    2.17    2.46    1.92    1.27    1.32    1.21    1.08       1    11
    12    0.94     1.5    1.63    2.32    2.97    3.29    1.83    1.27    1.34    1.21    1.05    1.03    12
    13    0.86    1.38    1.91    2.12    2.86    2.66    1.78    1.27    1.45    1.18    1.03    0.97    13
    14    0.94    1.21    1.91       2       3    2.86    1.92    1.35    1.45    1.18    1.03    0.89    14
    15    0.92    1.29    2.14    1.82     3.2    3.29    1.86    1.35    1.37    1.18       1    1.11    15
    16    0.92    1.21    2.14    2.09    3.26    2.97    1.81    1.32    1.32    1.18       1    0.89    16
    17    1.11    1.38    2.46    2.06     3.8    2.34    1.83    1.38    1.32    1.18    0.97    0.81    17
    18    1.11    1.41    2.34    2.06    3.57    2.43    1.83    1.49    1.32    1.16    0.95    0.78    18
    19    1.56    1.85    2.09    1.85    3.54    2.57    2.11    1.32    1.32    1.18    0.95    0.73    19
    20    1.28    2.24    1.69    1.97    3.17    2.86    1.78    1.27    1.34    1.18    0.97     0.7    20
    21    1.03    2.18    1.66     2.5    3.11     2.6    1.67     1.3    1.42    1.13       1     0.7    21
    22    1.22       2    1.83    2.68    2.57    2.37    1.47    1.46    1.42    1.11       1    0.65    22
    23    1.17    1.65    2.91    3.09    2.37     2.4    1.39    1.43    1.42    1.11    0.97    0.65    23
    24    1.22    1.71    2.34     3.5    2.34    2.49    1.56    1.35    1.39    1.13    0.97    0.62    24
    25    1.53    1.94    2.14    2.94    2.31    2.29    1.97    1.32    1.32    1.13    0.97    0.62    25
    26    1.36    1.97    1.91    2.74    2.51    2.31    1.86    1.54    1.32    1.11       1    0.65    26
    27    1.44    2.06    2.03    2.38    2.49    2.37    1.58    1.57    1.32    1.11       1    0.68    27
    28    1.44    1.97    1.83    2.74    2.17    2.43    1.56    1.51    1.32    1.13    1.08    0.84    28
    29    1.28    2.09       2    2.29    2.17    2.14    1.78    1.38    1.29    1.11    1.03    0.89    29
    30    1.14    2.76    1.63    2.09       -    2.03    1.81    1.32    1.29    1.13       1    0.89    30
    31    1.33       -    1.57    2.21       -    2.03       -     1.3       -    1.13       1       -    31
```

Figure A2.6   HYDRO25 daily data format.



```
B1H004
1963    1   31
 1       .0 -
 2       .0 -
 3       .0 -
 4       .0 -
 5       .0 -
 6       .0 -
 7       .0 -
 8       .0 -
 9       .0 -
10       .0 -
11       .0 -
12      1.6 -
13       .7 -
14       .2 -
15       .1 -
16       .1 -
17       .1 -
18       .1 -
19       .1 -
20       .1 -
21       .1 -
22       .1 -
23       .1 -
24       .1 -
25       .2 -
26       .2 -
27       .1 -
28       .1 -
29       .1 -
30       .1 -
31       .1 -
B1H004
1963    2   28
 1       .1 -
 2       .1 -
 3       .0 -
 4       .0 -
 5       .0 -
 6       .0 -
 7    -99.9 M
 8    -99.9 M
 9       .0 -
10       .0 -
11       .1 -
1
```

Figure A2.7   An example of ACRU single data format.

2.1.7.3 Parameter files

Appendix 1 discussed the parameter files, for each of the modules that require a parameter file in HYDRO25. The files defined as parameter files in this study do not necessarily have a module's parameters but have details about the module such as the rainfall data file name, the files to add, the evaporation data and all the information required about the module when the model runs.

2.2 Building the model for the Doring River case study

2.2.1 Simulation objectives in the Doring River case study

This study aimed to generate information that could be used to decide on the following development proposals:

(1) The maximum area of irrigated land that can be successfully developed for irrigation in the Koue Bokkeveld (KBV) area without providing additional storage.

(2) The possibility of irrigation at Aspoort using Doring River run-off

(3) The best combination of irrigation options for the KBV and Aspoort areas, with an additional storage at Aspoort. This scenario looks at the size of the irrigation area at Aspoort and the size of the Aspoort Dam then seeks to maximise its irrigation potential.

In this study only the hydrological implications were evaluated using the model HYDRO25. The study also aimed to use the most up to date hydrological inputs including recent developments in the catchment.

2.2.2 Physical conceptualisation

This stage of model development involved recording the physical design of the Doring River water system. The physical design is represented in a network diagram that describes the natural system. The network diagram also gives the relationships between the modules and how they should be entered in the model. The schematic illustration in Figure A2.8 shows the model schematisation.

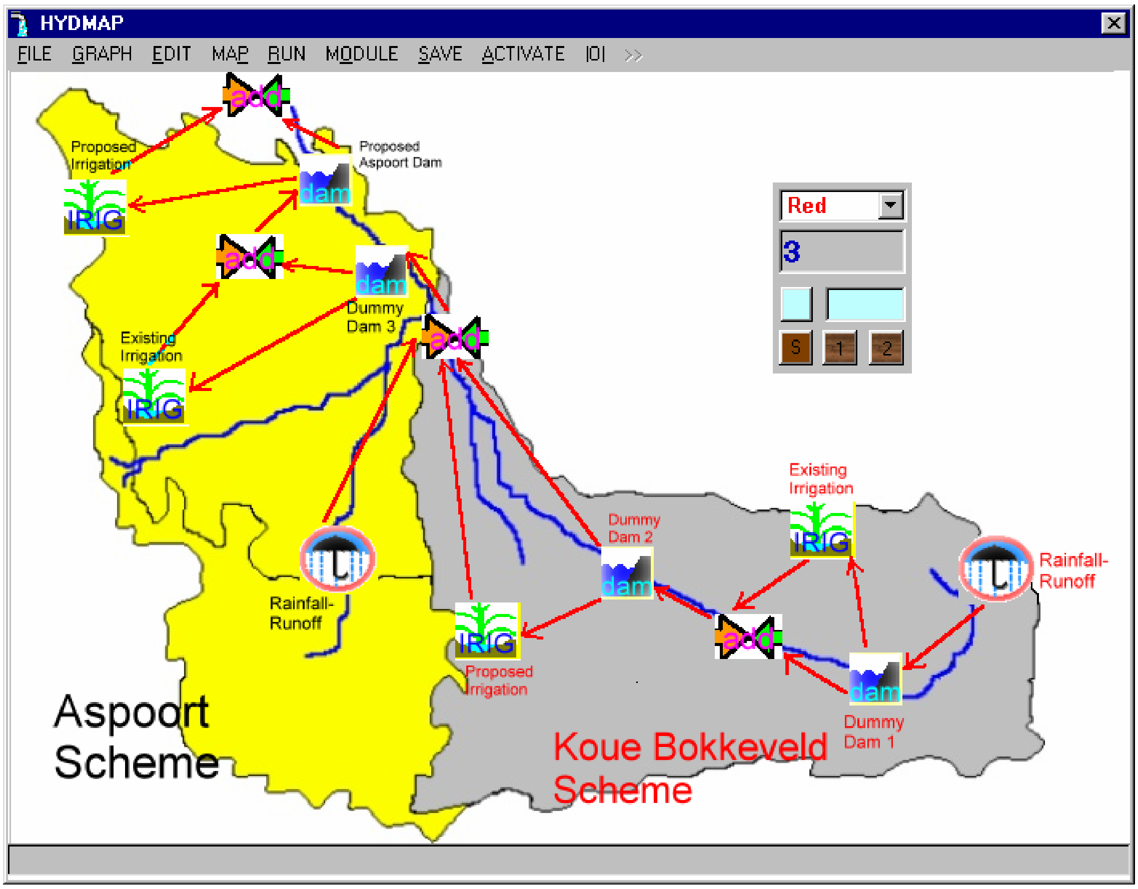


Figure A2.8 Doring River model schematisation.

The physical conceptualisation describes the pathway to a solution in a way that allows the modeller to develop a numerical solution on the computer. It communicates the necessary details of the solution including organisation, structure and relationships between the modules used for creating the elements of the solution. The physical model system was used to enter the electronic network in the computer. The main user interface will display modules in the same order as the sequence in which the network is resolved during a model run.

2.2.3 Model network and module relationships

The model simulated the catchment in a modular approach through component module blocks that described the different events in the catchment. The inter-relationships of the modules were set in the system network description file and the parameter files that contain information about each module. The parameter files were discussed in Appendix 1 for each of the modules in HYDRO25. Table 6.1 shows the network file contents as they were set up in the main user interface.

The main user interface does not show all the information in the water system's network file. Of major importance are the names of the parameter files associated with each routine. To see the parameter file names used for each module, an additional window is available that is accessed by pressing the enter key while in the module interface. In building up the model for the upper Doring catchment the positioning of the modules had to follow the precise order that allowed them to obtain inputs from other modules in time for the next step of the simulation. In the upper Doring River system two simulation systems were used, one for the calibration and another for determining the irrigation supplies without the dams. In the simulation, the irrigation modules and the runoff modules should be placed before the modules using their inputs. In the case of the upper Doring system, the modules FLOWADD and the RES25 modules used the outputs from runoff and irrigation simulations. The linking of the modules and the transfer of information between the modules, and between the model and the user, is a function of text files. The files are stored in the computer in a single directory for each run and have no effect on subsequent runs of other catchments if their files are stored separately.

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