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 (m³) 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 m³ (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 m³ 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 $500 \times 10^{12}$ (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, DTM, 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, DTM,
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.
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 coordinating 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>
<thead>
<tr>
<th>Physical Units or Level (Spatial Scale)</th>
<th>Important water related problems and issues</th>
<th>Advisory groups, Decision-Makers and Implementation Agents</th>
<th>Relative Ease of Implementing IWRM at this level</th>
</tr>
</thead>
<tbody>
<tr>
<td>1) World</td>
<td>-Greenhouse effects</td>
<td>-International Organisations e.g. IUCN, WHO, ICOLD</td>
<td>Almost Impossible</td>
</tr>
<tr>
<td></td>
<td>-Climatic changes</td>
<td>-Symposiums and International Forums, e.g. Lome convention</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Increasing water demand</td>
<td>-International Courts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Virtual water transfers</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Threats of water wars</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-International Legislation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>2) Region e.g. SADC, European Union (EU)</td>
<td>-International Waters and Legislation</td>
<td>-Regional Organisations and Institutions e.g. SADC, EU</td>
<td>Very Difficult</td>
</tr>
<tr>
<td></td>
<td>-Water quality control</td>
<td>-Internationals tribunal and courts</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-large projects e.g. Lesotho Highlands Water Project</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Standards of practice</td>
<td></td>
<td></td>
</tr>
<tr>
<td>3) Country</td>
<td>-Legislation</td>
<td>-Government Departments</td>
<td>Moderately Difficult</td>
</tr>
<tr>
<td></td>
<td>-Institutions</td>
<td>-Water Engineering Institutions</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Large projects</td>
<td>-Research Organisations</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Neighbouring countries</td>
<td>-Stakeholder groupings</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Pollution control</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Resource sustainability assessments</td>
<td></td>
<td></td>
</tr>
<tr>
<td>4) Basin and Catchment</td>
<td>-Implementation of Legislative tools</td>
<td>-Government Provincial or Regional Departments</td>
<td>Easy</td>
</tr>
<tr>
<td></td>
<td>-Demand points and ecology</td>
<td>-Catchment councils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Large and Small projects</td>
<td>-Town and provincial councils</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Pollution</td>
<td>-Private establishments and landowners</td>
<td></td>
</tr>
<tr>
<td>5) Rivers and Tributaries</td>
<td>-Flow Characteristics</td>
<td>-Town and Provincial Councils</td>
<td>Relatively the easiest for implementing IWRM</td>
</tr>
<tr>
<td></td>
<td>-Demand points and other users (nature)</td>
<td>-Water User groups</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Pollution monitoring and control</td>
<td>-Government representatives</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Storage facilities</td>
<td>-Individual researchers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Water loss: seepage and evaporation</td>
<td>-Pollution Control Officers</td>
<td></td>
</tr>
<tr>
<td></td>
<td>-Water projects</td>
<td>-Private firms</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Individual water users</td>
<td></td>
</tr>
</tbody>
</table>
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.
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,
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
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 complementarity 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).](image)

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 rainfall 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 km² do not have reliable rainfall gauges. The recommended rainfall network distribution in ACRU is that a maximum of 25 km² 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
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).
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 90º 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 infiltrometry 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 dolomitie 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

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,
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.

![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 1,855 (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 1,700 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).

<table>
<thead>
<tr>
<th>Weather Instrument</th>
<th>Station order</th>
<th>1st</th>
<th>2nd</th>
<th>3rd</th>
</tr>
</thead>
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<tr>
<td>Stevenson screen</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Max- and min thermometers</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Dry- and wet bulb thermometers</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>(Y)</td>
</tr>
<tr>
<td>Thermohygrograph</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>(Y)</td>
</tr>
<tr>
<td>Thermograph</td>
<td></td>
<td></td>
<td></td>
<td>(Y)</td>
</tr>
<tr>
<td>Standard 127 mm raingauge</td>
<td></td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Pressure plate anemometer</td>
<td></td>
<td>Y</td>
<td>(Y)</td>
<td>(Y)</td>
</tr>
<tr>
<td>Anemometer</td>
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<td></td>
<td>Y</td>
</tr>
<tr>
<td>Sunshine recorder</td>
<td></td>
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<tr>
<td>Barograph</td>
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<td>Y</td>
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</table>

(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 Welbedach Dam which carries over 15 million tonnes of sediments per year. DWAF (1997a) reported that the Welbedach dam reservoir capacity was reduced from 114
millions 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 directly 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).](image)

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.
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:

- Experienced 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 are 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.)

<table>
<thead>
<tr>
<th>Income category</th>
<th>Agriculture</th>
<th>Domestic</th>
<th>Industrial</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low Income</td>
<td>89</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>Low middle income</td>
<td>77</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Upper middle income</td>
<td>73</td>
<td>12</td>
<td>15</td>
</tr>
<tr>
<td>High income</td>
<td>40</td>
<td>15</td>
<td>45</td>
</tr>
</tbody>
</table>

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
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.

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 km². 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.