The implementation of an environmental decision-making support system: the Mooi River Catchment as a case study

by

Sarah Louise Currie

Thesis submitted in fulfilment of the requirements for the degree
Philosophiae Doctor
in Geography and Environmental Studies
at the Potchefstroomse Universiteit
vir Christelike Hoër Onderwys

Promotor: Professor A.B. de Villiers
Assistant Promotor: Dr I.J. van der Walt

Potchefstroom 2001

ACKNOWLEDGEMENTS

I would like to thank the following people and organisations who have been of assistance to me during the course of the research and compilation of my PhD.

- My supervisor Professor Braam de Villiers, whose unwavering faith and commitment to the 'cause' sustained me through the duration of the research. Especially during the long, seemingly endless hours of editing. I am eternally grateful to you for your support.
- Mark Dent, Reinier de Vos, Rajesh Nundlall and James Thorpe of the Computing Centre for Water Research (CCWR) without whom the research would have been impossible. Thank you for sharing your expertise, your time and your humour.
- Maria de Villiers for proof reading the final draft of my thesis. I learnt so much about the complexities of the English language.
- David Currie for proof reading earlier drafts of the document and for assistance with respect to structure and layout.
- Catherine Currie for the assistance on locating references for the Mooi River Catchment, of which there are numerous.
- North West Province Department of Tourism, Environment and Conservation for financial assistance and in particular Mr Deon Swart who genuinely believed in my philosophy towards the environment and supported the initiative
- Dr Kobus van der Walt for his help as my assistant promoter
- Dr Leslie Stoch for providing access to much of the available data pertaining to the Wonderfonteinspruit and for the time spent trying to 'explain' the complexities of the region.
- The Honours students of 1998, Roux Meter, Chris Botha, Daleen Opperman and Luisa de Sousa, for their assistance in capturing data and field evaluations for the Mooi River Catchment.
- Toni Bodington for cartographic assistance, layout and design
- Celeste Clark, for her longstanding years of friendship and support
- John and Seonaid Paterson, my cousins, for the loan of their computer while doing corrections in Scotland - I don't know if EDSS will ever be the same without Iain and Fionnghuala playing in the garden in the background shouting Auntie Squarah.
- To my family both near and far, and in particular Mum and Dad for the moral support and assistance through the many long years as a perpetual student. Especially for their assistance with respects to printing while I was in Scotland. Never has the world been such a small place. Mum and Dad, I am now finally finished!

ABSTRACT

The aim of the study is to create an interactive, real time environmental decision making support system for broad spectrum applications using public domain software that is affordable, and adaptable to the majority of water managers in South Africa. No formal evaluation and review of environmental decision making support systems exist in South Africa. The study contributes to the advancement of science in that the literature is reviewed to determine the relevance of environmental decision making support systems in South Africa. From the insight obtained from the literature review, an environmental decision making support system for a specific South African catchment is developed and implemented. The system needs to provide a tool for integrated catchment management to facilitate 'best practice' management. Aspects which have been included concern the complexity of water resources, integrated catchment management approaches, factors influencing the water resource, policy frameworks and the water law.

In order to achieve these aims, an extensive theoretical understanding of water resource management, integrated catchment management and decision support systems was required. Insight into the broad spectrum of applications and the complexity of the water resource problem was determined. On this basis, the relevant water users were defined and the factors affecting the water resource ascertained. The process and development of integrated catchment management are discussed in relation to the role they play in future water management in South Africa, taking into account policy frameworks and principles applicable to South Africa. The theoreticai framework, thus far, has been concerned primarily with water resources, processes and policies associated with the resource. Henceforth, the development and design of decision support systems are appraised and the implementation of an interactive, real time environmental decision making support system determined.

In order to determine whether an environmental decision making support system can be developed and customised for river catchments as a tool for integrated catchment management to facilitate 'best management' practices, an interactive, real time environmental decision making support system is devised and evaluated by means of a case study in the Mooi River Catchment. An empirical interactive, real time environmental decision making support system using public domain software for the Mooi River Catchment is available for viewing and interaction on the Internet at the site http://www.ccwr.ac.za.

The results of the study show that the creation of an interactive, real time environmental decision making support system is possible to facilitate the integrated catchment management approach using public domain software. Customisation of the environmental decision making support system is possible for river catchment.

The environmental decision making support system for the Mooi River Catchment is operational and creates a new way to structure and involve researchers, stakeholders, specialists and managers in environmental management in the Mooi River Catchment. Results highlight the environmental decision making support systems ability to operate within the Mooi River Catchment and provide a means to manage the environmental resources.

The Hydrological Simulation Programme - Fortran (HSPF) is capable of simulating the continuous, dynamic nature of the hydrological regime and water quality processes of the complex Mooi River Catchment. While the Watershed Data Management (WDM) supplies a data warehouse facility and a systematic approach to the storage and retrieval of data. The establishment of an environmental database to be used and customised in the Integrated Catchment Information System (ICIS) provides a Graphic User Interface (GUI) through which spatial time series characteristics of the data can be viewed.

Implementation of the environmental decision making support system in the Mooi River Catchment case study provides a prototype environmental decision making support system that can be used as a protocol by Catchment Management Agencies (CMAs) for the implementation of integrated catchment management around the country.

OPSOMMING

Die doel van hierdie studie is die daarstelling van 'n interaktiewe intydse omgewingsbestuurstelsel vir besluitnemers. Die stelsel moet in staat wees om 'n wye verskeidenheid toepassings te hanteer en moet saamgestel word deur gebruik te maak van bekostigbare rekenaarsagteware wat vryelik en gratis beskikbaar is vir die gebruik deur waterbestuurders in Suid-Afrika. Daar is tans geen formele evalueringsmeganisme en of oorsig oor omgewingsbestuurstelsels vir besluitnemers nie. Hierdie studie lewer 'n bydrae op hierdie terrein in die sin dat sodanige stelsels geëvalueer word deur gebruik te maak bestaande van literatuur. Gegrond op hierdie literatuurstudie is so 'n omgewingsbestuurstelsel vir bestuurders daargestel. Hierdie stelsel is ontwerp vir 'n dreineringsbekken en daar is daarin geslaag om dit suksesvol te implementeer. Een van die vereistes wat aan die stelsel gestel word is dat dit in staat moet wees om gesonde beginsels vir geïntegreerde bekkenbestuur te implementeer. Aspekte wat in die ontwerp en toepassing van die stelsel aandag verdien, is ondermeer die ingewikkeldheid van waterbronne, geïntegreerde bekkenbestuur, faktore wat waterbronne beïnvloed, beleidsraamwerke asook die Waterwet.

Om hierdie doelstellings te bereik, is dit veral noodsaaklik om 'n deeglik begronde teoretiese agtergrond met betrekking tot waterbestuur, geïntegreerde bekkenbestuur en besluitnemings-ondersteuningstelsels te bekom. Verder is die nodige kennis in verband met die spektrum van moontlike toepassings, asook die kompleksiteit van die gebruik van waterhulpbronne beskryf. Die verskillende gebruike en gebruikers van water is bespreek en die impak van gebruikers op die hulpbron beskryf. Die proses en ontwikkeling van geïntegreerde bekkenbestuur word ook bespreek om aan te toon hoedanige rol dit speel in die toekomstige bestuur van water in Suid Afrika. Dit is gedoen met in ag name van die beleidsraamwerke en beginsels wat in die land van toepassing is. Hierdie teoretiese raamwerk was veral gemoeid met die bronne van water, prosesse en beleid wat daarop betrekking het. Die volgende afdeling van die teoretiese agtergrond is toegespits op die ontwikkeling, ontwerp en implementering van intydse besluitnemingstelsels vir omgewingsbestuur.

In die volgende afdeling van die proefskrif is daar gepoog om vas te stel of dit moontlik is om sodanige geïntegreerde intydse omgewingsbestuurstelsel vir besluitnemers wat betrokke is by dreineringsbekkenbestuur daar te stel. Dit is gedoen met die oog daarop om gesonde omgewingsbetuursbeginsels te implementeer. Vir die doel is die Mooirivier-opvanggebied gekies. In hierdie empiriese studie is aangetoon dat dit wel moontlik is om die gestelde doelwitte te bereik en die resultaat is weens die omvangrykheid van die stelsel en die hoeveelheid gegewens wat gebruik

is om die proefneming na behore te doen, nie in gedrukte formaat beskikbaar nie. Die uitkoms van die studie is vir besigtiging, sowel as vir gebruik op 'n interaktiewe wyse, beskikbaar op die Internet en wel by die webwerf http://www.ccwr.ac.za.

Die uitkoms van hierdie studie dui daarop dat dit wel moontlik is om geïntegreerde omgewingsbestuurstelsels te ontwerp wat op 'n intydse interaktiewe wyse bedryf kan word. Die stelsel wat ontwerp en suksesvol geïmplementeer is, stel bestuurders in staat om met behulp van sagteware wat gratis en vryelik bekombaar is op die internet, geïntegreerde bekkenbestuur te bedryf. Die aanpassing van sodanige stelsel vir gebruik in enige ander dreineringsbekken is ook moontlik.

Hierdie geïntegreerde bekkenbestuurstelsel vir die Mooirivier is reeds operasioneel en dit skep nuwe moontlikhede vir navorsers , belanghebbendes, deskundiges en bestuurders in die opvanggebied. Die uitkoms van die studie toon dat die stelsel geskik is vir gebruik en dit verskaf 'n nuwe wyse waarmee omgewingshulpbronne bestuur kan word.

Die Hidrologiese Simulasie Program (in Fortran) HSPF is in staat om al die nodige simulasies vir die uiters komplekse Mooirivieropvanggebied uit te voer. Die dinamiek van die hidrologiese regime en die prosesse betrokke in die bepaling van waterkwaliteit word deurlopend gesimuleer. Die gegewens wat benodig word om die stelsel te bedryf word deur middel van 'n databestuurstelsel wat bekend staan as die "Watershed Data Management" (WDM) beheer. Die stelsel is in staat om die gegewens op 'n sistematiese wyse te berg en beskikbaar te stel vir gebruik. Die databasis wat daargestel is vir die omgewingsaspekte van die geïntegreerde bekkenbestuur inligtingstelsel (ICIS) kan deur middel van 'n grafiese gebruikers koppelvlak (GUI) opgeroep word. Die ruimtelike tydreekseienskappe van die data kan met behulp van hierdie koppelvlak visueel voorgestel word.

Die resultate wat in hierdie studie bereik is, toon duidelik aan dat die geïntegreerde omgewingsbestuurstelsel wat vir die Mooirivier ontwerp en geïmplementeer is, in die toekoms as 'n prototipe kan dien vir bekkenbestuur agentskappe (CMAs) vir implementering in ander dele van die land.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter Two

Chapter Four

Chapter Five

CHAPTER ONE

1 INTRODUCTION TO THE IMPLEMENTATION OF AN ENVIRONMENTAL DECISION-MAKING SUPPORT SYSTEM

1.1 Introduction

An increasing awareness over recent years concerning water resources has lead to new approaches towards achieving sustainable exploitation of such water resources internationally (Larsen *et al.*, 1997). As a consequence, water management in South Africa is currently standing at a crossroad, due in part to the new South African water and environmental laws which highlight the need for effective water resource management, but also as a result of recent environmental world trends. South Africa is classified as a semi arid (Figure 1.1), semi industrialised and multicultural country with developing and developed populations (Stoffberg *et al.*, 1992) and, as such, water has become both the sustaining factor for life and a limiting resource for development in southern Africa.

The management and protection of water resources in South Africa have been identified as key areas of concern to the South African government and are strongly addressed in the new National Water Act (Act No. 36 of 1998). In order to attain the sustainable use of water for the benefit of all users, integrated management strategies and the delegation of management functions to a regional or catchment level has been implemented. These steps are a logical and irreversible response to the forces of environmental management and protection that are currently prevalent in South Africa and the rest of the world.

There are few scientific and environmental groups in South Africa that have the ability to develop a world class environmental decision support system. The country needs to produce such a world class system that is affordable and adaptable to the needs of the majority of water managers in South Africa. Such a system should exhibit the key characteristics of compatibility, inter-operability, functionality and flexibility, affordability and co-ownership. The new Water Act and the documents preceding it have highlighted the need for an integrated approach to the management of water resources. The new Water Act states that integrated catchment management fosters co-operation and consensual techniques to managing water, land and other interdependent attributes of every catchment through the provision of pertinent information.

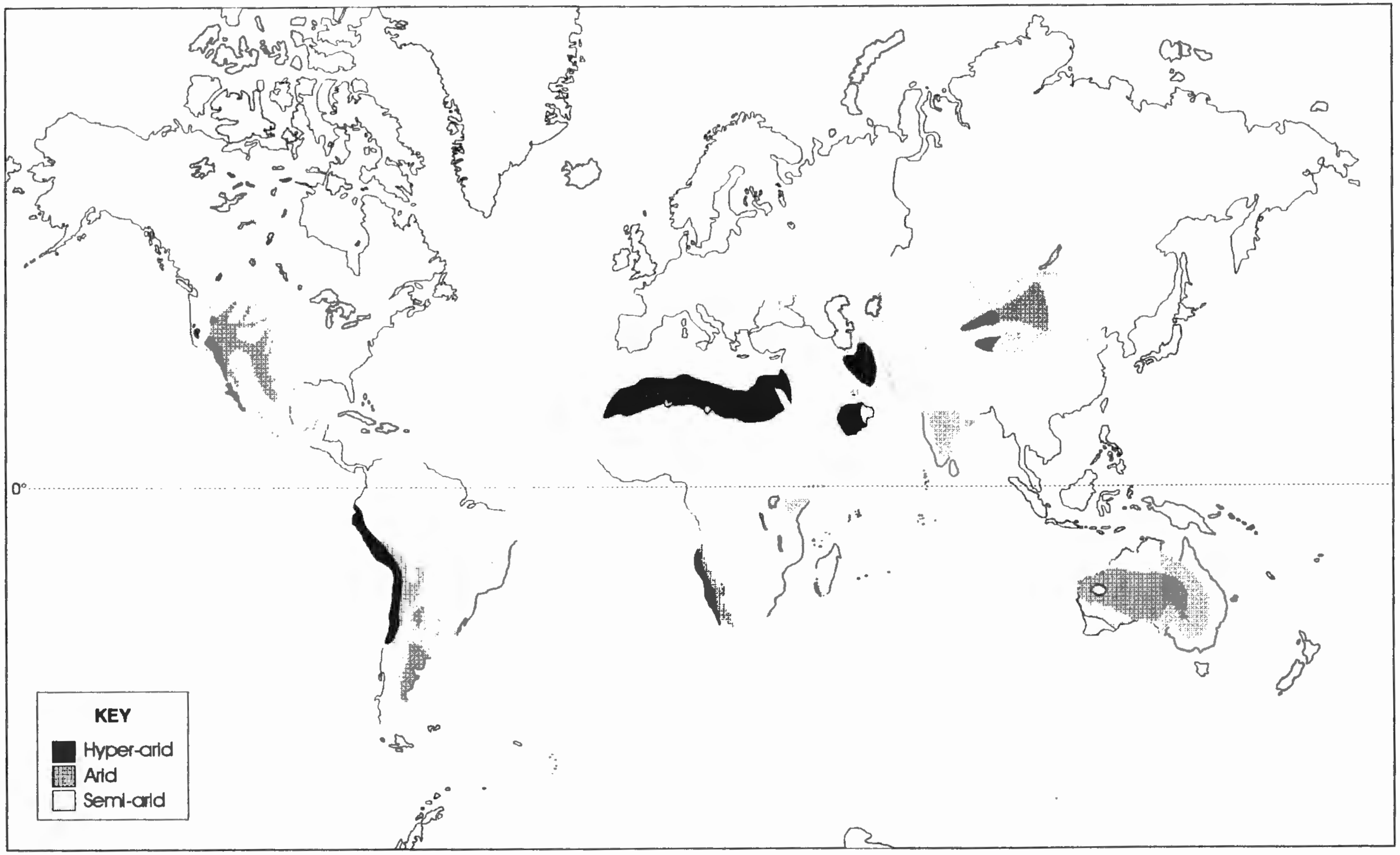

Figure 1.1: The global distribution of arid Tand semi arid lands (modified after Thoms and Walker, 1992 and Davis *et al.*,1993).

The rationale for the creation of an environmental decision making support system (EDSS) arose from the fact that catchment management studies tend to concentrate on certain 'catchment specific problems'. The complex nature of the natural systems and the conflict between competing sectional interests add to the difficulties of catchment management studies. Data collected for these studies are usually piecemeal and unavailable for any subsequent research due to ownership problems. No study currently exists which describes all the components of EDSS within the view of developing a user friendly, functional, flexible and compatible system from public domain software that is controlled by the stakeholders. In the initial chapters such a review is given and an appropriate system derived.

The creation and implementation of an EDSS should prevent such problems, as data will be available from a centralised, shared database, using public domain software. The software needs to be affordable to facilitate the meaningful communication amongst all stakeholder representatives. To control and manage catchment environmental problems, an integrated EDSS will be devised and implemented using public domain software for public use. A case study in the Mooi River catchment will serve as a prototype to test the validity of the system.

1.2 Problem statement

Can an EDSS in the public domain be developed and customized for river catchments that will provide a tool for integrated catchment management in order to facilitate environmental 'best practice' management?

1.3 Aims

The aims of the project are:

- ❑ to create an interactive, real time EDSS, taking the complexity of water resources, integrated catchment management, factors influencing the resource, policy frameworks and the water Act into account for broad spectrum applications; and
- ❑ the evaluation of the system by means of a case study.

1.4 Objectives

The following objectives were defined:

One: determine the broad spectrum of applications, acquire insight into the complexity of the water resource problems, define the relevant water users and determine the factors influencing the water resource.

To achieve objective One

- ❑ identify water as a resource and highlight water problems associated with the scarcity of the resource;
- ❑ identify factors affecting the water resource and identify and discuss aspects related to the relevant water users.

Two: define the integrated catchment management (ICM) process, discuss its development and determine its role in future water management for South Africa taking policy frameworks and principles applicable to South Africa into account.

To achieve objective Two

- ❑ highlight the need for a holistic approach to water management and challenges for ICM;
- ❑ define and review the current approaches to ICM, the historical development in South Africa and the development of sustainable catchment management structures;
- ❑ develop the catchment management process and review the ICM approach;
- ❑ identify policy frameworks and principles for South Africa and issues of the new Water Act.

Three: to determine and understand the development and design of DSS as a tool for the implementation of an interactive, real time EDSS.

To achieve objective Three

- ❑ highlight, define and analyse the origins and historical foundations of DSS;
- ❑ identify factors contributing to the acceptance of DSS;
- ❑ discuss a systems approach and a decision support systems approach to DSS and their role in the decision making process;
- ❑ review and ascertain the scope and use of the various models of decision making;
- ❑ identify a framework analysis and highlight the need for appropriate data support of DSS;

- establish the role of group decision for DSS;
- identify and discuss the various components and tools available for EDSS; and highlight misconceptions related to the use of DSS.

Four: to test the feasibility of the above objectives, the development and implementation of an interactive, real time EDSS by means of a case study in the Mooi River catchment is performed to serve as a blue print for broader applications.

To achieve objective Four

- introduce and identify the complexities of the Mooi River Catchment and highlight the decision support system approach;
- identify the aims of the decision support approach and establish ideals of an EDSS for the catchment;
- establish the environmental setting and environmental problems associated with the catchment;
- ascertain the methodologies for software selection, Hydrological Simulation Programming Fortran (HSPF), Watershed Data Management (WDM) file system, ArcView GIS (Geographical Information Systems) and Integrated Catchment Information System (ICIS) as tools for decision support;
- acquire data from various sources and input the data into the WDM file system, simulate and calibrate the Mooi River Catchment using HSPF;
- develop and populate an environmental GIS database for the catchment before incorporating the data into ICIS;
- develop and populate external databases for the catchment;
- identify and discuss the results highlighted by the implementation of an environmental decision support system for the Mooi River catchment; and denote recommendations and future prospects for the continued implementation and use of the EDSS in the Mooi River Catchment.

In order to fulfil the above objectives i.e. determining whether an EDSS can be developed and customised for river catchments as a tool for ICM to facilitate environmental 'best practice' management, an interactive, real time EDSS will be developed and sappraised by means of a case study in the Mooi River Catchment. To this end, theoretical frameworks relating to water resource management, ICM and DSS need to be established, such that the role of EDSS with respect to environmental 'best practice' management can be determined.

Chapter Two provides a background to water resource management in South Africa highlighting the water problems associated with the scarcity of and factors affecting the water resource as relating to the relevant water users. Thereafter, the future and policy framework for management of the water resource in South Africa, as identified by the ICM process is discussed in Chapter Three. Chapter Four establishes the theoretical framework and development of decision support systems as available tools for the implementation of environmental decision support systems. The creation and implementation of an interactive, real time environmental decision making support system by means of a case study in the Mooi River Catchment is addressed in Chapter Five. Conclusions and recommendations to the application are described in Chapter Six.

In addition to the written component of the thesis, an empirical study which demonstrates the EDSS for the Mooi River Catchment has been developed.

The EDSS can be viewed on the world wide web at the site http://www.ccwr.ac.za. and is discussed in greater detail in Chapter Five.

CHAPTER TWO

2. WATER RESOURCE MANAGEMENT IN SOUTH AFRICA: A BACKGROUND

2.1 Introduction

The water resource literature currently available appears to be somewhat dated. The possible reason for this is that the importance of water as a resource within South Africa was highlighted in the late 1980's and early 1990's. This is evident in the publication dates pertaining to this subject.

South Africa's mean annual precipitation (MAP) is calculated as 497 mm per year (O'Keeffe *et al.*, 1992), compared to a world average of 860mm per year (Alexander, 1985). In addition, rainfall is unevenly distributed, with 65% of the country receiving less than 500 mm of precipitation annually and 21% receiving less than 200 mm (Figure 2.1). In addition, mean annual potential evaporation rates for South Africa is exceptionally high. Lowest values occur in the Drakensberg and along the eastern and southern coastal areas region (< 1400 mm), increasing towards a high of > 3000 mm in the northwestern region of South Africa (Figure 2.2). The scarcity of water as a resource is highlighted in Figure 2.3 whereby the ratio between mean annual precipitation s(MAP) and mean annual runoff (MAR) is determined for different countries around the world. South Africa's ratio of 8.6% is one of the lowest ratios in the world, accentuating the need for water management strategies. Superimposed on the scarcity and uneven distribution of water resources are regional and temporal variations in rainfall. The broad regional climatological precipitation patterns for South Africa exhibit an eastern area of summer rainfall, a southwestern winter rainfall belt, a southern belt of year round rainfall and an arid western region (Figure 2.1) (Dent *et al.*, 1989). Furthermore, the strong seasonal nature of the precipitation and the high average annual potential evaporation, which ranges between 1100 and 3000 mm (Figure 2.2) (Schulze *et al.*, 1997), contribute towards the complex nature of water resource management in South Africa.

Knowledge and understanding of long term precipitation cycles, that is between 18 and 20 years, are important to ensure that interpolations of water supplies measured during only one portion of the cycle are avoided. Long term precipitations cycles as determined by Dyer (1976), for the summer precipitation regions, are depicted in Figure 2.4. Coupled with the high rainfall unpredictability dominated by the convective rainfall and high evaporation rates common in South Africa, water resources need to be more effectively managed to ensure sustainable use for future generations.

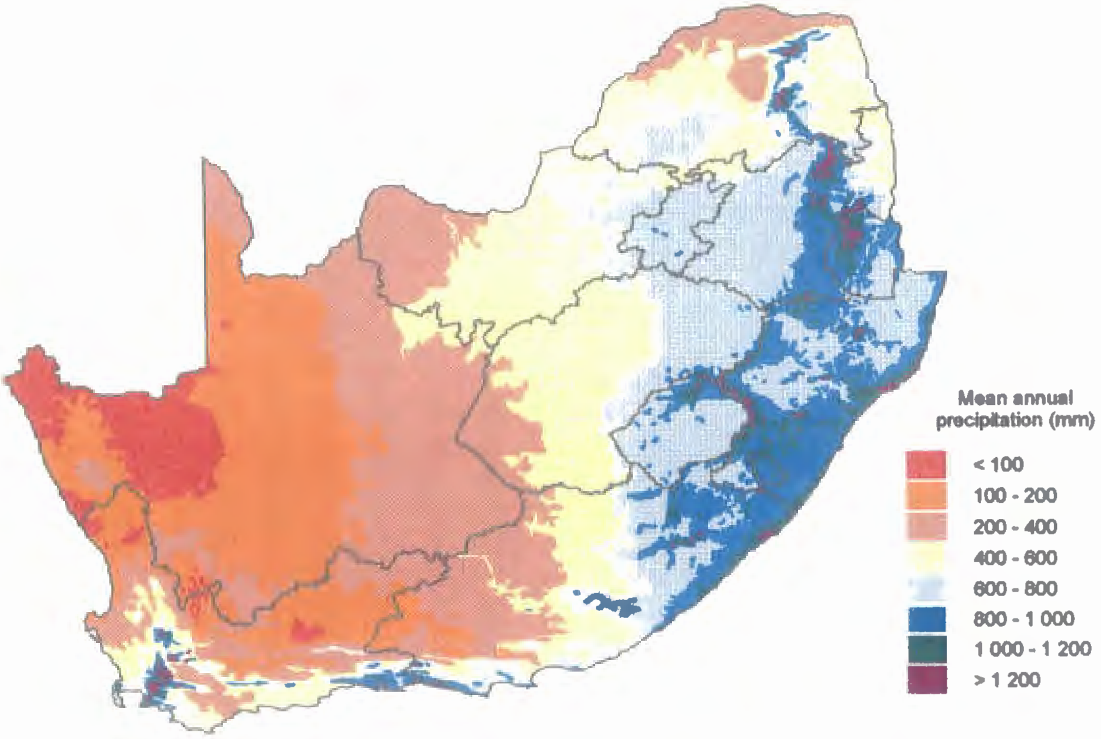

Figure 2.1: South African mean annual precipitation (mm) (modified after Dent, Lynch and Schulze, 1989)

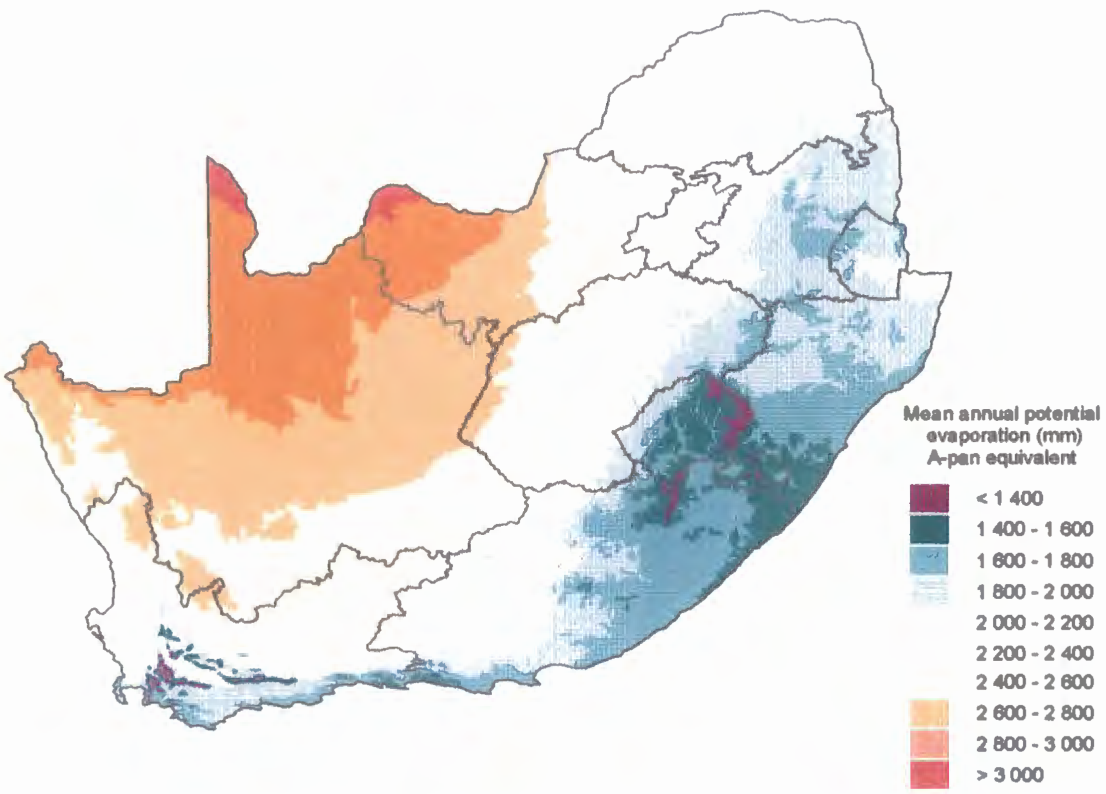

Figure 2.2: South African mean annual potential evaporation (mm) (modified after Schulze, Maharaj, Lynch, Howe and Melvil-Thomson, 1997)

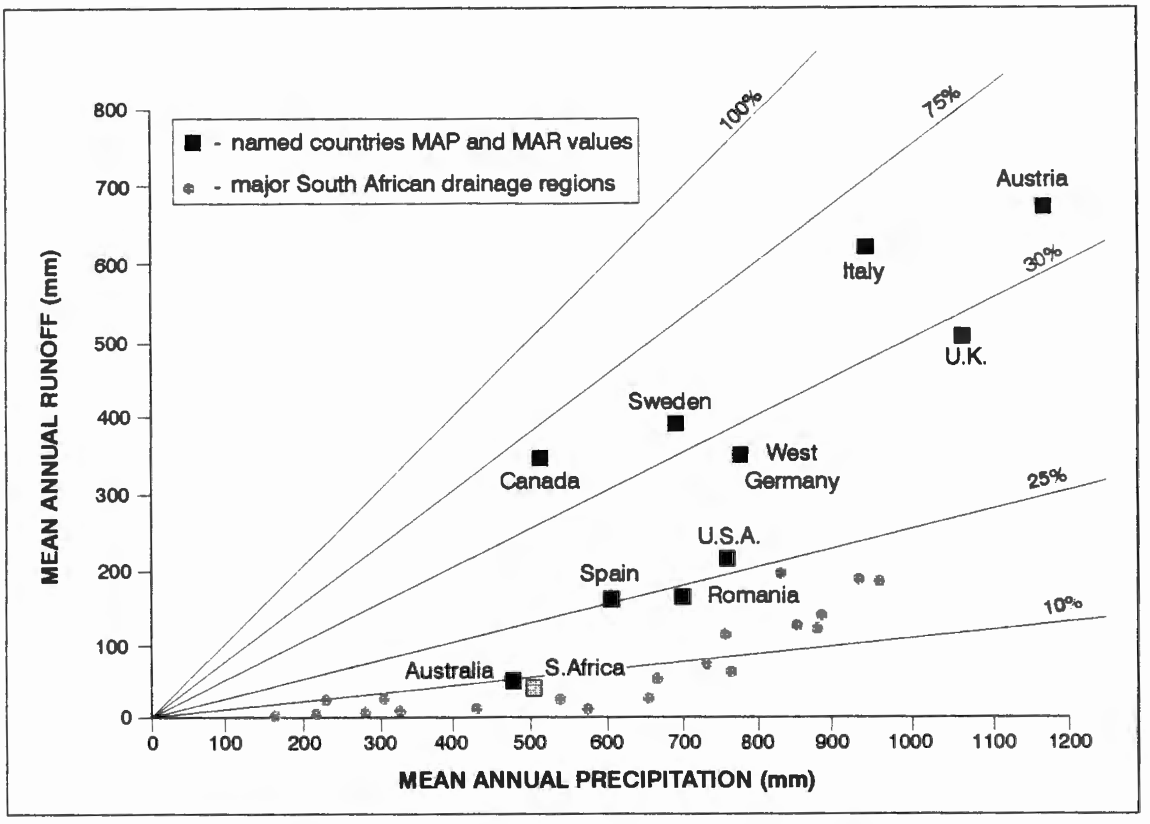

Figure 2.3: MAP and MAR for selected representative countries in the northern and southern hemispheres with twenty of South Africa's major drainage regions (modified after Alexander, 1985).

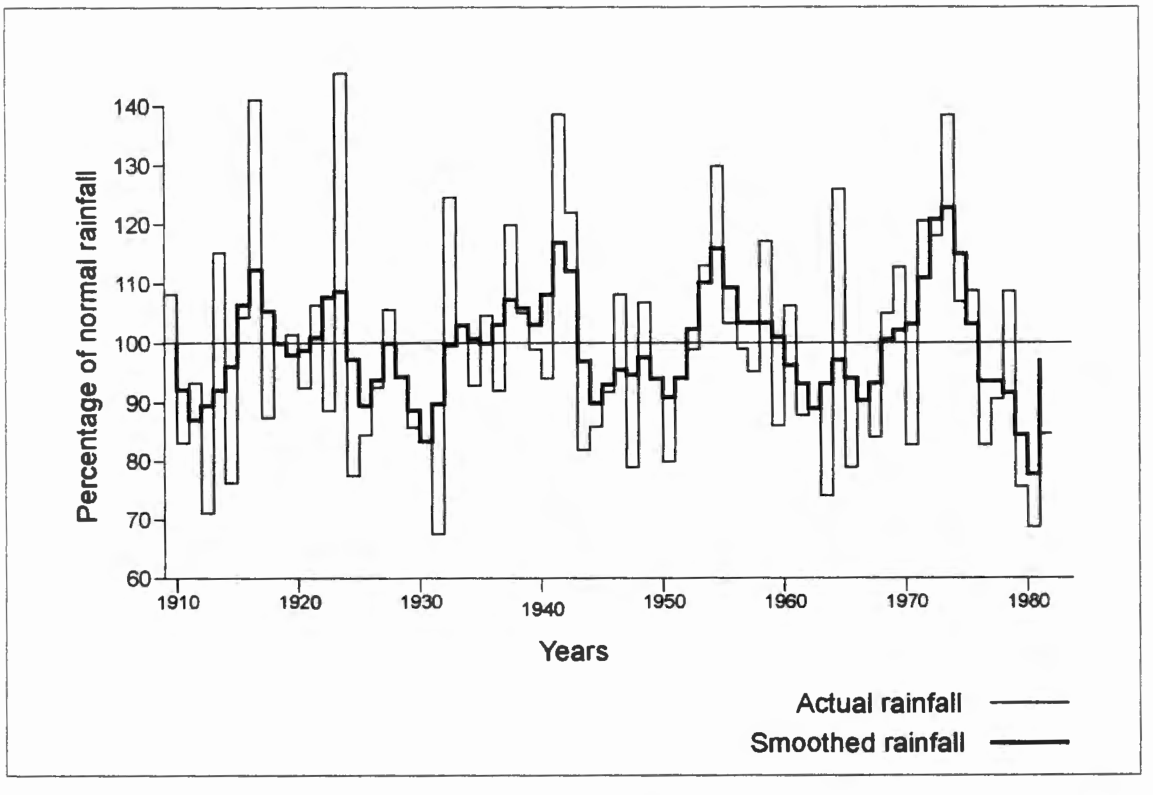

Figure 2.4: Long term precipitation cycles for the summer precipitation region of South Africa (modified after Dyer, 1976).

2.2 Water as a resource

The Department of Water Affairs and Forestry (DWAF) is the custodian of water resources in South Africa, and has a national responsibility to ensure that the basic water needs of the people are met. DWAF is also compelled to address current needs of water users and provide for the anticipated growth in the national economy (DWAF, 1996a).

The DWAF, therefore, plays a crucial leadership role and carries the responsibility to initiate national strategies for long term water resource management. At a national or central government level, the DWAF provides leadership, technical guidance and a resource management framework, based on important principles such as standards, environmental protection and waste minimisation. Thereafter, provincial governments and local authorities are expected to address local and regional issues as well as taking appropriate responsible decisions within the management framework (DWAF, 1996).

Exploitable water resources in South Africa are confined to rivers, artificial impoundments and ground waters due to the lack of natural freshwater lakes in the country. Total runoff from South Africa is estimated at 53 500 million m^3 per annum of which about 33 000 million m^3 (62 %) could practically be exploited (DWAF, 1986). In addition to the surface water resource, there are substantial ground water reserves. However, recharge estimates are uncertain, and so, therefore, are the renewable resource values. Recharge estimates of between 16 000 and 37 000 million m^3 have been suggested (O'Keefe *et al.*, 1992), but only a small quantity of this amount may actually be economically recoverable. Values of 5 400 m^3 per annum may represent the realistic potential maximum ground water use, which relates to approximately 16.4 % of the annual exploitable surface runoff from rivers.

Water demand as a consequence of population growth is an important consideration with regard to the management of the water resource in South Africa (Davies *et al.*, 1993c). Research undertaken by Davies and Day (1986) illustrate projected water demands and population growths for South Africa (Figure 2.5). Although dated, findings of the research are still beneficial as it highlights both the projected demands for water directly correlating to the size of the population. Results show that with respect to the highest population estimations and the highest water demand estimations, total surface resource will be exhausted just after the turn of the century while additional available groundwater resources ensure a water resource base only until 2014. Obviously, such estimations have as yet not transpired. Results from the StatsSA 2001 census should clarify the current situation with regards to population growth and water demand.

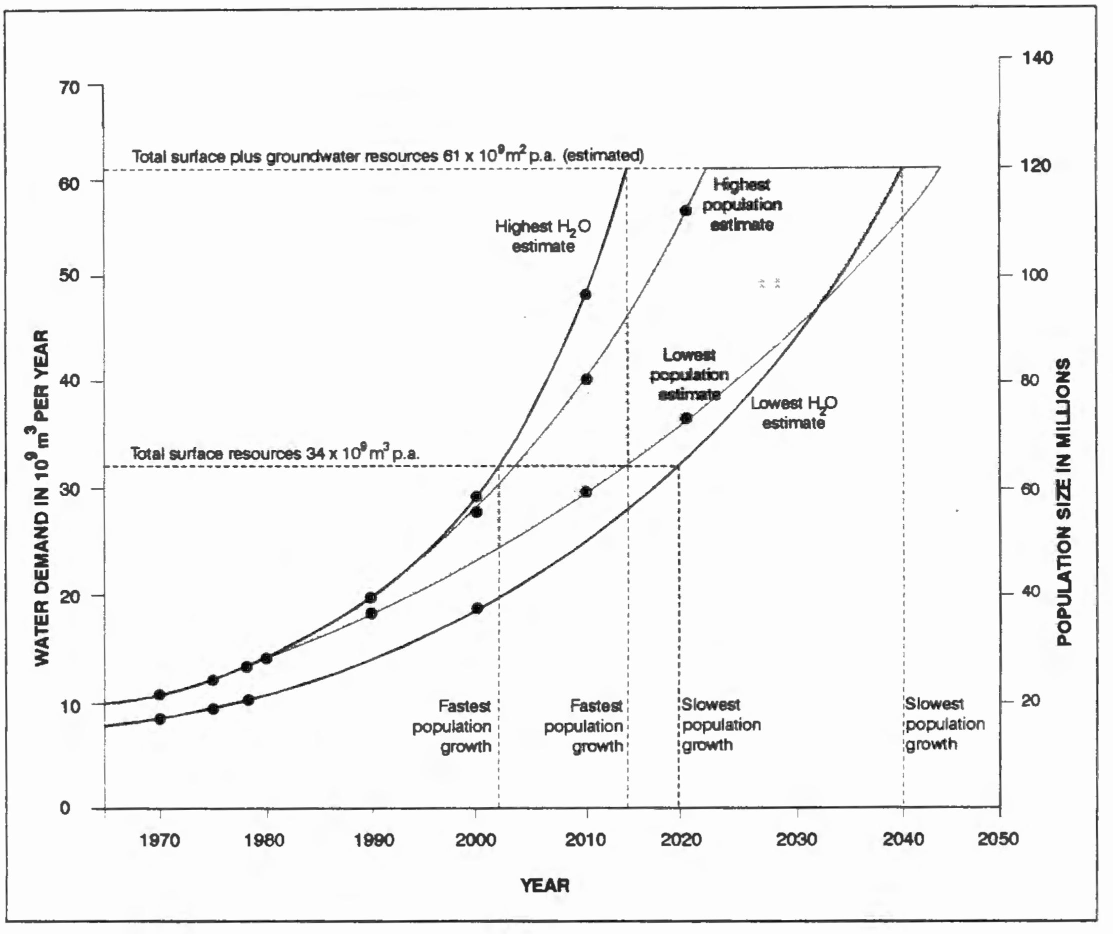

Figure 2.5: Projected water demands and population growth for South Africa until 2050 (modified after Davies and Day, 1986).

2.3 Factors affecting the water resource

The conditions, water quality and biota of a water body are the product and reflection of events and conditions in the catchment and, as such, water resource conservation needs to be managed on a catchment basis. In this way, one part of a rivers' catchment is not isolated and subjected to extensive control, while other parts of the catchment area are not comprehensively and uniformly managed by the same authority (O'Keeffe *et al.*, 1992). Land use and the modifications of natural vegetation play a vital role in determining the proportions of rainfall that reach the various components of the catchment system, and the runoff to rainfall magnitude.

In southern Africa, the trend for perennial rivers to become intermittent, with no flow during the drier months, can be attributed to land mismanagement (Whitlow, 1983) and is a consequence of land use and vegetation changes in the catchment.

Most catchment systems exhibit a wide variety of environmental problems caused by natural factors as well as the multiplicity of water users. A case study of the Mooi River Catchment is undertaken based on the complexities of this system. The following paragraphs describe water users in general, however, the majority bear relevance to the Mooi River Catchment.

2.4 Water users

The major uses and demands of water in South Africa for 1990, as estimated in 1986 by the DWAF (O'Keeffe *et al.*, 1992) and predicted changes expected by 2010 are tabulated in Table 2.1. The largest water user in South Africa has traditionally been the agricultural sector, which account for 52.4% of direct water usage. Present water-use amounts to nearly 50 % of available runoff, and ground water utilisation is likely to rise to 67 % by 2010.

Table 2.1: Mayor types of water use in South Africa for 1990 (modified after DWAF, 1986)

Demand sector	1980 (million $m^3\ y^{-1}$)	%	1990 (million $m^3\ y^{-1}$)	%	2000 (million $m^3\ y^{-1}$)	%	2010 (million $m^3\ y^{-1}$)	%
Direct use								
Municipal and domestic	1 516	9.3	2 281	12.0	3 220	14.4	4 477	17.3
Industrial	1 031	6.3	1 448	7.6	2 043	9.1	2 961	11.4
Mining	466	2.9	511	2.7	582	2.6	649	2.5
Power generation	282	1.7	444	2.3	779	3.5	900	3.5
Irrigation	8 504	52.2	9 695	50.9	10 974	48.9	11 885	45.9
Stock watering	262	1.6	288	1.5	316	1.4	358	1.4
Nature conservation	178	1.1	182	1.0	187	0.8	191	0.7
Indirect use								
Forestry runoff reduction	1 284	7.9	1 427	7.5	570	7.01	1 700	6.6
Ecological use, estuaries and lakes	2 768	17.0	2 767	14.5	2 767	12.3	2 767	10.7
Total	16 291	100.0	19 043	100.0	22 438	100.0	25 888	100.0

Predictions indicate that while the amount of water used for irrigation may continue to increase slowly, domestic and industrial water use will increase much more rapidly (Davies and Day, 1986 Figure 2.5) due to rapid urbanisation and associated reticulation schemes responsible for the supply of water to the previously disadvantaged populations in South Africa (Davies *et al.*, 1993c). Although these predictions appear to be comfortably within the limits of available water, spatial and temporal availability of water need to be considered along with the cautions that recharge rates of groundwater resources are not conclusive and that the groundwater resource is also limited. The Gauteng area already uses far more than 100 % of locally available water. Additional water has to be imported from the Usutu and Tugela Rivers (Petitjean and Davies, 1988a; Petitjean and Davies, 1988b) . Further, water demands rarely diminish in times of drought and as such, water managers have to plan for sufficient water storage or imports to account for worst drought scenarios.

Other major water users include the indirect use demand sector. The indirect use sector includes ecological use, forestry, estuaries and lakes. The acknowledgement of the ecological use of water is an encouraging and farsighted recognition by the DWAF that water must be retained in rivers to sustain the riverine, estuarine and lacustrine ecosystems. Although the listings for ecological use as outlined in Table 2.1 are, at present, largely theoretical, urgent efforts are being made by DWAF and the provincial governments to assess and quantify the ecological water requirement of rivers and estuaries (O'Keeffe, 1990).

The multiple use of rivers can eventuate in severe environmental impacts (O'Keeffe, 1986; Davies and Day, 1986). Consumptive use removes water from the system, while non-consumptive use often produces effluent. Moreover, practices not directly related to the use of water may have a detrimental impact on the river, in that the river condition is always a reflection of all activities within the river, as well as in the catchment area (Rabie and Day, 1992).

2.4.1 Use of water for industry

Although industry, including mining and power generation, accounts for only 16% of South Africa's current direct water use, its impact is disproportionately high because effluents often contain toxic substances and other pollutants (Rabie and Day, 1992). One of the main effluent problems associated with industry is the modification of thermal conditions downstream. In some instances, stream temperatures may be increased by 10 to 20 °C (Dallas and Day, 1993). Related to this is the fact that thermal pollution is almost always intermixed with other forms of pollution such as chemical pollution, and it is the toxicity associated with these chemicals that may increase significantly in conjunction with the elevated temperatures (Duffus, 1980; Förstner and Wittmann, 1981).

Mining is of great importance to the national economy. The industry demands a high assurance of water supply, using almost 3% of all water available in South Africa. Mining effluents, produced through the use of water as a medium for mineral abstraction, often contain highly toxic chemical compounds, resulting in severe environmental impacts on rivers (Dallas and Day, 1993). Drainage occurs not only from the mine itself, but also from the waste rock dumps and tailings dam areas (Funke, 1990). The pollution sources contain high concentrations of sulphides and/or sulphate salts which are associated with most ore bodies (Dallas and Day, 1993). The high sulphates and low pH levels result in the formation of hydrogen sulphide. Moreover, seepage from gold / uranium tailings dams are characterised by extremely low pH values (Wells, 1987), high sulphate contents and elevated trace metal concentrations which may lead to an increase in pollution levels in nearby rivers (Förstner and Wittman, 1981). To highlight the problems that can be experienced in the Mooi River Catchment case study, the hydrochemistry of effluents from gold mining wastes from the vicinity, namely the West Wits and West Rand is documented in Table 2.2 (Förstner and Wittman, 1981).

Table 2.2: The hydrochemistry of effluents from gold mining wastes (mg l^{-1}) (modified after Förstner and Wittman, 1981)

	pH	So_4	Fe	Mn	Zn	Cu	Pb	Cr	Ni	Cd	Co
Normal river water	6 - 9	0.011	0.1	0.007	0.01	0.003	0.0005	0.001	0.001	0.0005	0.0002
West Wits	1.7	11.13	550	206	26.00	5.4	0.290	4.00	6.40	0.052	3.30
West Rand	3.7	2.95	3	18	4.68	1.22	0.081	0.02	1054	0.007	2.25

Characteristics of surface water systems exposed to prolonged gold mining activities are described by Pulles *et al.*, (1996) and include:

- strong point source effluent discharging saline and acidic effluent into the surface water environment;
- old, non-operational slimes dams (often poorly or un-rehabilitated) in or close to natural water courses, resulting in substantially high saline and acidic diffuse pollution sources;
- extensive old surface infrastructure (including various defunct shafts) which cannot be properly maintained due to lack of staff and funds - typically associated with declining ore grades; and
- ongoing reworking of surface sand and rock dumps.

Jones *et al.* (1989) highlight the significance of mineral pollution from mining activities in the Vaal Barrage, where high salt loads in the Vaal River are attributed to seepage from gold mine tailings and sand dumps.

Industries other than mines account for over 7% of the total water use (DWAF, 1986). Many manufacturing industries generate a variety of effluents that eventually find their way to the rivers and are detrimental to the environmental health of the river (Rabie and Day, 1992). Such industries include the chemical industry (Council for Scientific and Industrial Research, 1991), the dairy industry

(NATSURV 4, 1989), the fertilizer industry (Council for Scientific and Industrial Research, 1991), the food canning industry (Council for Scientific and Industrial Research, 1991), oil refineries (Singh and Gaur, 1989), the poultry industry (NATSURV 9, 1989), pulp and paper manufacture (Davis *et al.*, 1988), the red meat industry (NATSURV 7, 1989), the tanning and leather finishing industry (NATSURV 10, 1989) and the textile industry (McKee and Wolf, 1963; Council for Scientific and Industrial Research, 1991).

Power generation, which accounts for approximately 2% of total water use in South Africa, is also harmful to the riverine environment in that power plants require water, abstracted from the river, for cooling purposes. The return of the water, after use by the power plant, to the river tends to raise the temperature of the river water, thereby adversely affecting the natural river habitat. Riverine habitats are also affected by hydro-electric power plants, which bring about fluctuations in downstream flow that are quite unlike natural seasonal fluctuations to which the biotas are accustomed (Rabie and Day, 1992).

2.4.2 The use of water for agriculture

Agriculture has always played an important role in the economy of South Africa, and as a result has always claimed the majority of water resources in South Africa. By 1965, consumption for irrigation and stock watering had reached more than 83% of the total water consumption (Rabie and Day, 1992). This percentage has now dropped to approximately 67% of direct water use despite an increase in water used for irrigation (Table 2.1) (DWAF, 1986). The effects of agriculture on the riverine environment depend on the type of agriculture and farming practices. Farming practices such as land clearing, burning, irrigation, ploughing, livestock handling, fertiliser and biocide application, logging and afforestation with exotic species all contribute to the negative effects of agriculture on the water system (Dallas and Day, 1993). Livestock practices can alter runoff patterns due to trampling soil and plants. In the case of intensive 'feedlot' farming, high production of excreta can detrimentally affect the quality of the water through an increase in nutrient production (McColl and Hughes, 1981).

Environmental degradation due to agriculture also includes excessive abstraction for irrigation. Irrigation is particularly consumptive in South Africa due to the intensity of use as a consequence of highly subsidized water tariffs on government water schemes and irrigation water boards of the past. No river can withstand unlimited abstraction of water without losing its viability as a functioning ecosystem (Rabie and Day, 1992). The destruction of riparian vegetation ultimately leads to accelerated soil erosion due to the destabilisation of river banks (Dallas and Day, 1993). Soil loss increases the silt load of the rivers which has the effect of reducing the water quality (Fourie and Görgens, 1977), and storage capacity of dams. Malpractices such as the cultivation of wetlands, burning of the veld and over-grazing, result in deterioration of the vegetative cover.

Aquaculture, or the commercial cultivation and harvesting of aquatic organisms (Safriel and Bruton, 1984), has certain negative effects on water use. Although aquaculture is non-consumptive, it may still lead to pollution since the quality of the water which is returned to the stream in question is usually degraded. Such negative effects include waste food and excreta (Bergheim and Selmer-Olse, 1978) which settle on the river beds.

2.4.3 The use of water by urban and rural settlements

Municipal and domestic water consumption utilise between 12% and 14 % of South Africa's available water. This has a considerable impact on rivers, due to the fact that the effects are concentrated on to relatively small confined areas (Rabie and Day, 1992). Migration of rural inhabitants into urban areas places increasing pressure on resources within the urban areas (Dallas and Day, 1993). Runoff in urban areas, particularly after heavy rainfall, contains pollutants which ultimately make their way into local streams and rivers (Novotny and Chestes, 1981). Urbanisation is characterised by an increase in impervious areas, decreased natural storage capacity and canalisation of rivers. These factors result in increased runoff volume and discharge rates which often contain a variety of pollutants (Dallas and Day, 1993). Generally, low flows are lower and high flows higher than under natural conditions due to the reduced contribution of ground water and the reduced interchange between surface and ground water. The 'initial flush' at the start of the rainfall event transports approximately 40% of pollutants (Weeks, 1982). In addition, urban complexes also generate large amounts of waste and urban refuse which can result in eutrophication, increased biochemical oxygen demand and a reduction in faunal diversity of the river system (Rabie and Day, 1992).

In the rural areas and informal communities of South Africa, populations tend to concentrate near watercourses. In these regions, water abstraction, use and return to the source are often not adequately controlled, while sewage and effluent remain untreated (Rabie and Day, 1992). Urbanisation of rural areas is characterised by an increase in impervious areas, decreased natural storage capacity and canalisation of rivers thus resulting in increased runoff (Dallas and Day, 1993). Moreover, the impact of such communities usually extends to the vegetation in the catchment and the riparian vegetation is destroyed.

2.4.4 The effects of development and infrastructure

The main effects associated with road and dam engineering and construction, relate to the physical disturbance of rivers and catchments. Such effects may be far reaching from temporal, spatial and ecological perspectives (Dallas and Day, 1993). The most detrimental affect resulting from road construction is the increase in suspended solids and deposited sediment (Taylor and Roff, 1986) in the river system. Similar effects can be associated with the constructions of dams. Increased suspended solids and deposited sediment occurs as a consequence of earthworks and clearing of vegetation (Davey *et al.*, 1987). Such activities have often been responsible for the degradation of estuaries (Davies *et al.*, 1993a). An additional detrimental activity associated with engineering and construction is canal construction or channel modification. Various problems include the replacement of heterogeneous bed and banks of a natural river with many different habitats (pools, riffles and backwaters) with smooth concrete. Canalisation of a river course isolates the river from groundwater input, aquatic ecology feeding sites are removed and migration patterns interrupted. Removal of riparian vegetation increases bank instability, with increased erosion, increased light penetration and increased temperatures (Dallas and Day, 1993).

2.4.5 Recreation

Recreational activities are often practised in, on and along inland waters such as rivers and dams (Rabie and Day, 1992). Such activities include swimming, angling, canoeing, power boating, sailing and hiking. A considerable recreational industry has been established to support these activities. Recreation is dependant on high standards of water quality. There are also negative effects associated with recreation, such as the destabilisation of river banks, the destruction of riparian vegetation, and littering (Rabie and Day, 1992).

2.4.6 Environmental conservation

A competing water demand, only recently recognised, is that of environmental management of estuaries, lakes, wetlands, riverine habitats and conserved areas (Roberts, 1983). Such management, contrary to the other water use categories, should have no negative impact on rivers since it's very aim is conservation (Rabie and Day, 1992). The estimated water allocation needed for this somewhat diffuse use category, sometimes referred to simply as 'the needs of the environment' has been variously estimated as amounting to between 10 % (or 2160 million m^3 y^{-1}) and 13% (or 2947 million m^3 y^{-1}) of the total water demand (DWAF, 1986).

2.5 Chapter summary

The scarcity of water as a resource in South Africa is highlighted in Chapter Two. South Africa is a water scarce country with an uneven distribution of water resources and regional and temporal variations in rainfall. An understanding of the integrated nature of water resource management is therefore necessary to ensure that water resources are effectively managed. Effective management will safeguard the sustainable use for future generations as water demands increase due to the consequences of population growth. However, the conditions and water quality of the water resource are the product and reflection of events within the catchment. In this way, the holism of land and water degradation, together with the impacts on water and land users, cannot be separated or managed independently of each other. Factors affecting the water resource include the various uses and demands of water such as industry, mining, power generation, agriculture, rural and urban settlements, development and infrastructure, recreation and environmental conservation. All these factors contribute significantly towards the need for an integrated approach to water management and is discussed in greater detail in Chapter Three.

CHAPTER THREE

3. INTEGRATED CATCHMENT MANAGEMENT: THE FUTURE AND POLICY FRAMEWORK FOR MANAGEMENT OF THE WATER RESOURCE IN SOUTH AFRICA

3.1 Introduction

The ICM approach is reviewed in Section 3.1 to 3.9. Thereafter, the policy frameworks for water management in South Africa will be discussed.

In following the current trend of a more holistic approach to management of the environment (DWAF, 1996), DWAF recognises that naturally occurring water can usually only be effectively and efficiently managed within a river basin or catchment area, as all aspects of the hydrological cycle need to be studied and managed (van Zyl, 1995). Based on this insight, integrated water resource management on a catchment basis has become the declared goal of water management at national, regional and catchment levels (Görgens *et al.*, 1998). Thus, all future projects relating to river catchments will adopt the ICM approach which expedites the interdependent roles of resource protection and resource utilisation.

It is well documented, that the water resource includes not only the water, but also the structural and biotic components of the aquatic ecosystem (MacDonald and Crawford, 1988; Davies *et al.*, 1993a; Davies *et al.*, 1993b; Banens *et al.*, 1994 and DWAF, 1996), the sustainability of which is dependant on the socio-economic, physical, chemical and biotic attributes and the interaction between them. Protection, utilisation and management of the resource must, therefore, be based on ecological principles, thereby relating to the management of the water quantity, water quality and physical and structural characteristics of the resource. This will provide an appropriate abiotic template which will ensure the integrity of the biotic component of the resource (DWAF, 1996). Water resource management responsibilities, therefore, need to include the three components of habitat, aquatic biota and water, as well as physical, chemical and ecological processes which link them to the aquatic environment (Davies *et al.*, 1993c). In this way, the holism of land and water degradation, together with the impacts on water and land users, cannot be separated or managed independently of each other. Co-ordination, planning and action are required at all levels from national government to the individual landowners (Görgens *et al.*, 1998).

3.2 Challenges for integrated catchment management (ICM)

The management of water resources in South Africa must implement an ICM approach based on a number of pertinent and relevant factors. These factors or focus areas, highlighted by Görgens *et al.* (1998) to facilitate in the implementation of integrated water resource management in South Africa, include:

- ❑ <u>the technical challenge</u>: range in scope from the deterioration of water quality as a result of physical developments and human activities (O'Keeffe *et al.*, 1992), to dictating strategic water resource planning and development initiatives at national and regional scales that facilitate the country's need to develop in a sustainable manner (Forster, 1992; Quibell *et al.*, 1997).

- ❑ <u>the need for people-orientated water management</u>: political changes in South Africa and the lack of trust and legitimacy of previous delivery systems for social services, have resulted in people feeling the need to participate in (van Veelen and van Zyl, 1995) and contribute to the decision making process (Maaren and Dent, 1995). Participation in planning and management aspects ensure that the concerns and requirements of stakeholders and the public are met and that the appropriate delivery of the resource is received.

- ❑ <u>water management at the catchment scale</u>: water resources that originate in and reflect conditions throughout a physiographically defined drainage area, known as a catchment (local scale) or a basin (larger scale with multiple catchments), are derived as a result of runoff from the surrounding slopes or groundwater recharge (O'Keeffe *et al.*, 1994). However, certain factors detract from the concept that the catchment and the river basin are ideal water management units:
  - catchments do not coincide with the administrative regions (DWAF, 1996).
  - difficulties may also arise in cases where inter-basin transfers cause water to cross catchment boundaries (Petitjean and Davies, 1988a; Petitjean and Davies, 1988b); and
  - a different type of complication stems from the fact that ecological systems often traverse the boundaries of different catchments and even large river basins, requiring unconnected sub-basins to be linked for ecological purposes (Davies *et al.*, 1993c).

On these bases it is evident that water management needs to be manifested at, and integrated across, many different scales ranging from local tributary sub-catchment scale through catchment and basin scales up to regional, provincial, national and international levels (DWAF, 1996).

- ❑ landuse within the catchment: impacts significantly on both the quality and quantity of the water resource as well as on the health of the aquatic ecosystem reliant on the resource (Dallas and Day, 1993). A continuum between the hydrological cycle, land use and aquatic ecosystem functioning therefore exists within the catchment delineation (DWAF, 1996).

- ❑ the need for integration: sub-catchments, catchments, river basins and inter-connected river systems provide a series of interlinking building blocks designed to support strategic water resource management imperatives that have to operate at scales across and beyond basin boundaries, yet still maintain sustainability (Vicory, 1995; DWAF, 1996; Görgens *et al.* 1998). In universal terms, different levels of integration are conceivable for the management of water resources, each, more comprehensive than the previous one (Görgens *et al.* 1998):
  - harmonious management of surface water and ground water, quantity and quality;
  - integrated water resource management require the mutual dependance of water and land management at the local catchment level to ensure sustainability, and upwards integration of strategic water management at scales beyond that of catchments;
  - integrated environmental resource management, which includes management of land, air, water and ecological resources, and also includes integrated pollution and waste control motivated by the understanding that all environmental resources are bounded by a web of inter-relationships which ultimately impact the water resources; and
  - integrated development management, which envisages the management of water, land and other environmental resources in harmony with economic and social development, motivated by the understanding that the development of industrialised human society can be sustained only if water and all other resources are managed in a sensitive and wise manner.

The ICM approach, believed by many to be the ideal, lies within the sphere of environmental resource management (Görgens *et al.* 1998). Below the ideal level, catchment management concentrates primarily on water and is thus viewed as an attenuated form of the ideal ICM. Above the ideal level, integration deals only indirectly with the catchment management context. Rather, it concentrates on the regional perspective of integrated development management in an industrial society. The catchment, therefore, may not be the logical geographical unit for regional planning and socio-economic development.

- statutory integration and the principles for the new Water Act: South Africa's new Water Act (Act No. 36 of 1998) arose as a result of the Governments acceptance of 28 fundamental principles and objectives, thereby guiding the subsequent process of the writing of the new Water Act. The following principles, relating to integration, are of particular relevance (DWAF, 1996a; Görgens *et al.* 1998):
  - Principle 15: Water quality and quantity are inter-dependant and shall be managed in an integrated manner, which is consistent with broader environmental management approaches
  - Principle 17: Water resource development and supply activities shall be managed in a manner which is consistent with the broader national approaches to environmental management
  - Principle 18: Since many land uses have significant impact on the water cycle, the regulation of land use shall, where appropriate, be used as an instrument to manage water resources within the broader integrated framework of landuse management
  - Principle 22: The institutional framework for water management shall as far as possible be simple, pragmatic and understandable. It shall be self driven and must minimise the necessity of state intervention. Administrative decisions shall be subject to appeal
  - Principle 23: Responsibility of the development, apportionment and the management of the available water resources shall, where possible and appropriate, be delegated to a catchment or regional level, in such a manner as to enable interested parties to participate

Although these principles have, in theory, been accepted as part of the National Water Policy for South Africa, their actuality within the practices of the new Water Act still needs to be demonstrated. The new Water Act has limitations in that the current view of ICM is confined to water resource management (Görgens *et al.* 1998).

- the limits of statutory integration: the factors of fragmentation, feasibility and institutional uncertainty within the statutory climate in South Africa, limit the integration of water, land and environmental management (Görgens *et al.* 1998). Due, in part, to the fact that water and land are classified under the broader concept of natural resources, South Africa's environmental, water and landuse legislation has, in the past, been severely fragmented (Rabie and Fuggle, 1992). Despite current reforms, however, fragmentation is likely to persist as the South African Constitution recognises water management and certain landuse related subjects such as mining, energy and land affairs as central government competencies, while other subjects to which landuse relates, such as agriculture, nature conservation, the environment, soil conservation, roads, urban and rural development and tourism, are rendered provincial competencies (Görgens *et al.*1998). The DWAF, therefore, has little control over landuse activities with the exception of forestry and certain aspects of mining and solid waste disposal.

The focus at operational level needs to be constricted to the local catchment scale. At this scale, it is feasible that a small number of variables can often account for a substantial portion of the water resource and land management challenges (Dallas and Day, 1993; Vicory, 1995).

Finally, integration is constrained by the need for a balance between the opposing top-down directive approach and bottom-up organic approach models of catchment management institutions or structures (Rogers *et al.*, 2000). Within the catchment management process a balance between these institutional extremes needs to be derived. However, the extent to which statutory promulgation of stakeholder-based catchment management processes is implemented, will impact the nature and extent of the integration of water management towards sustainability (Dent, 2000).

- the conceptual basis of ICM: the theory of ICM is founded on the belief that the different components of the hydrological cycle are intrinsically linked together. Each component is thus directly or indirectly affected by changes to the other components, thereby initiating integrated management rather than separated or detached units (Thomas, 1995; DWAF, 1996).

3.3 Integrated Catchment Management (ICM) defined

ICM is a systems approach to the management of natural resources, in particular water resources, within the confines of a geographical unit or catchment area of a single river system (DWAF, 1996). In its broadest sense, ICM is both a process, and an implementation strategy to achieve a sustainable balance between utilisation and protection of all environmental resources within a catchment (Görgens *et al.*, 1998). The advantage of such an approach is based on the ability to segment or divide the river system into logical or pragmatic management units, either at the catchment or sub-catchment scale, which can then be sectioned together to create a comprehensive management plan for an entire river basin (DWAF, 1996). For ICM to be successful, a sustainable society through stakeholder, community and government partnerships in the management process (Görgens *et al.*,

1998) needs to be developed. All aspects of the environment including economic and social issues need to be incorporated into the overall management philosophy, process and plan to ensure the optimum combination of sustainable benefits for future generations and the communities in the area of concern, whilst protecting the natural resources which are used by these communities and minimising possible adverse social, economic and environmental consequences (DWAF, 1996).

A true systems approach to ICM entails recognising that a disturbance made at one place in the system will translate to other parts of the system. Sometimes the effect on another part of the system may be indirect or buffered as a result of an inherent natural resilience to the disturbance and sometimes the effect will be direct, significant and may increase in magnitude as it moves through the system (Görgens *et al.*, 1998).

If the idea of a catchment as an integrated system is to be successfully adopted and implemented, then management of the catchment requires planning and enforcement of actions designed to maintain the system at a particular agreed upon status. Management actions, therefore, need to focus on the land to ensure that impacts of land-based activities on water resources are enforced to ensure adequate storage, distribution and rehabilitation where necessary. The selected series of management actions, debated by the stakeholders and communities to determine a preferred sequence of actions and associated consequences, would then be chartered as a catchment management plan which requires the formal approval of the Minister of Water Affairs (Quibell *et al.*, 1997). Responsibility and implementation of which would include a set of numerical and/ or narrative water environment objectives, derived such that the agreed status of the catchment water resources can be maintained (Görgens *et al.*, 1998).

ICM, therefore, provides:

- ❑ a philosophy which underlies sound natural resource management, on which a consideration of the whole natural system is based as well as a recognition that systems respond to disturbance or utilisation as systems, not as individual components in isolation from each other;
- ❑ a process in which both the community and government are involved in a 'people- orientated' partnership designed to achieve better natural resource management at the local catchment level. Thus taking into account the needs and ideas of the whole community; and
- ❑ a product or strategy which can be implemented and incorporates environmental, social and economic considerations based on a set of development objectives which are identified jointly by the community and the government.

The five basic principles outlined by the DWAF (1996) to ensure effective ICM include:

- a systems approach which identifies individual components and the linkages between them, as well as addressing the needs of both the human and natural systems;
- an integrated or holistic approach in which attention is directed towards principal issues of concern identified by all shareholders in the process;
- a stakeholder approach which recognises the importance of public participation, as well as government agencies, in an attempt to define all decisions around the conservation and use of natural resources which affect their lives;
- a partnership approach which fosters the search for common objectives, and defines the roles, responsibilities and accountabilities of each agency and individual who participates in the process of decision making; and
- a balanced approach where decisions designed to achieve a sustainable blend of economic development, protection of resource integrity, whilst meeting social norms and expectations, is given attention.

3.4 Current approaches to Integrated Catchment Management (ICM)

Water resource management and the development and implementation of technical, economic and management approaches to ICM have been adopted throughout the world to manage water resources on a sustainable basis with some notable successes and failures. In an attempt to avoid failure of the initiation of the ICM approach in South Africa, careful cognisance of the overseas experience is important. In this vein, a summary of current international approaches to ICM is discussed below to identify the successes, shortfalls and failures of those experienced by countries around the world and would form an appropriate basis for implementing ICM in South Africa (Forster, 1992; Quibell *et al.*; 1997).

In Australia, separation of commercial and non-commercial water sectors for catchment and water management is being initiated. Water authorities are regionalised and commercialised, thereby ensuring that the supply agencies have become bulk users of water and/or effluent dischargers, and are subject to the same licencing procedures as the other stakeholders or impactors in a catchment. Management of catchments and waterways is controlled by the Environmental Protection Authority (EPA) (Blake, 1993) which focuses primarily on identifying, controlling and ameliorating land use activities which have impacted, or are impacting on water resources (Blackmore, 1995). Community involvement in land and water management is also paramount in the whole ICM procedure as a means of identifying problems and planning and implementing management decisions and actions (Thomas, 1995).

The watershed approach in North America focuses on the protection and management of the quality of natural resources in a river basin to ensure clean, safe drinking water to the population of North America and comprises three key components namely, a geographic focus where the watershed boundaries, including groundwater recharge areas, is used as the primary planning unit; the development and use of sound scientific data, tools and techniques to facilitate the planning and management process; and partnership and stakeholder involvement in designing and implementing watershed goals (EPA, 1998).

ICM in the United Kingdom in contrast to those approaches previously mentioned is more of a 'top-down' model as the environmental agency acts on behalf of the communities involved in the area concerned (House, 1995). This concept can be successful provided the regulatory agency has sufficient expertise, and the appropriate technical and financial resources are available (Matthews, 1995). Contrasts between the United Kingdom and South Africa include firstly, the fact that Britain is not a water scarce country and thus the pressure of water demand is reduced and secondly, the general public have a considerable degree of trust towards regulatory authorities, therefore, reducing the need for stakeholders to participate actively or have close involvement in the decision making process (NRA, 1995).

ICM in France is the responsibility of the Minister of the Environment, under the auspices of the Department's Water Directorate which is based on five principles, namely, surface and underground water resources unity; water is managed within the context of drainage basins; all activities which influence the quantity and quality of the water must be integrated in the management of water; there must be financial solidarity between all categories of water users ie. people who abstract water as well as those who discharge effluent; and there needs to be close co-operation between parties and agencies involved in, or associated with, water management (Sironneau, 1993; Sironneau, 1994; Talec, 1995). Although seemingly cumbersome and inept compared to other ICM approaches, the French are one of the few countries in the world that have successfully implemented the ICM approach successfully with regards to water resource management in the country; to such an extent, that their concepts are being realised in other countries around the world.

Implementation of the ICM concept in Namibia and Zimbabwe has had limited success as much of the attention is spent on resolving the complex issues of large, shared river basins such as the Zambezi, Okavango, Kunene and Orange Rivers where negotiations have been intense and often hostile in those regions where water resources are scarce or where civil war prevails. Although these countries acknowledge the fact that the ICM approach offers the most effective solution to water resource management, very little has been achieved beyond the development of conceptual plans due to the inherent political, economic and social instability as well as the need for sufficiently skilled personnel and a lack of technical and financial resources (DWAF, 1996).

South Africa is, therefore, in the unique situation in that the insight and knowledge gained from local and international experiences of ICM can be implemented in the South African context. In this way, the ICM plan initiated in South Africa can draw on all the positive aspects from around the world and avoid all the failings and shortfalls that the different countries have experienced. It is important to note, however, that even although many ICM approaches have been adopted around the world, the ICM procedure implemented in South Africa needs to be tailor-made for what is best for the country. Considerations, such as the desire of the South African government for communities to play a more active role in decision making needs to be included in the ICM approach (DWAF, 1996). Concerning critical natural resources, the improvement of collaboration and liaison between the different government departments at a local and national level, and the implementation of complementary legislation pertaining to resource management by the various government departments need to be addressed and included in the ICM process for South Africa (Görgens *et al.*, 1998).

The issue is further complicated by the fact that resource management initiatives in South Africa are fragmented and there is an urgent need for synthesis. In statutory terms, ICM is driven by the DWAF, the emergence of a national land-care movement is driven by the National Department of Agriculture, and the establishment of conservation and conservancies are driven by the National Department of Environment Affairs and Tourism and the Parks Boards. The line-function structures of government, however, seem to militate against the effective inter-departmental networking and current directions of statutory development in South Africa preclude the achievement of integration of environmental resource management as a 'government programme' in the short to medium terms (DWAF, 1996; Görgens *et al.*, 1998).

Instead, a national policy that binds all relevant national and provincial government departments and agencies, as well as local authorities, to work together for sustainable development, and provision for procedures to ensure that consensus is formed regarding resource management objectives and strategies, are needed. However, this concept requires political will and commitment from the highest level through to the 'local' level, as well as deep commitment to extensive interaction and communication between state departments and with catchment stakeholders (Görgens *et al.*, 1998).

3.5 Historical development of integrated catchment management (ICM) in South Africa

The ICM approach was first adopted by the DWAF in South Africa in the 1980's as a means of managing catchments in the former Eastern and Northern Transvaal provinces to assess the quantity and quality of available water resources, identify the needs of different water use sectors, predict likely future developments and develop holistic approaches and plans for water resource management in the catchments of concern, for example the Sabie River Basin Study (Hollingworth and Mullins, 1995), with varying degrees of success.

With each ensuing catchment study, more experience was gained and areas and issues of concern came to the fore (Breen *et al.*, 1995). Such issues include the necessity to improve the process of public participation, including clear definition of the roles and responsibilities of all participants; the need to develop appropriate institutional structures which could facilitate communication, promote information sharing at all levels, assist in the decision making process, and allow the definition of clear responsibilities and accountabilities for implementation; the need to involve all water users in the planning and implementation phases of water resource management; and the need for the DWAF to take responsibility for leadership and the provision of technical guidance in a management framework for water resource management (Forster, 1992; DWAF, 1996; Quibell *et al.*; 1997).

3.6 Developing sustainable catchment management structures

For sustainable catchment management structures to develop in a practical and effective manner, legal requirements for the institutional model outlined in the National Water Policy have to be compiled within the different catchments in the country. To this end, the ideal model for catchment management structure needs to be compared with that proposed by the National Water Policy to evaluate the relevant legal aspects.

The ideal institutional model for catchment management would be based on a system of integrated environmental resources management within the framework of an integrated legal system, catchment boundaries and by a management structure which represents not only all stakeholders, but also all relevant government authorities (Görgens *et al.*, 1998). The achievement of the ideal of sustainability, however, depends not only on the setting up of appropriate institutional management structures, but also hinges on the streamlined inter-relationships between all environmental management components, the achievement of which is as much a process of education and human development, as a legally prescribed procedure or plan.

In contrast to the ideal model for catchment management, the proposed alternatives from centralised control to representative management consisted of two main components during the reform of the Water Act, namely, a public consultation process and a research process. Legal requirements are thus paramount for the establishment of catchment management structures for all catchments in the country; and need to include legislation which (DWAF, 1996a):

- directs the establishment of a management structure for each catchment;
- prescribes the procedure for establishment;
- enables and directs the Department to assign primary functions to the structures including the establishment of databanks; and
- set criteria, the compliance with which will direct and enable the Department to transform catchment management structures into catchment authorities

3.7 The catchment management process

Regardless of whether the catchment management process starts off in a state-driven, directive manner, or in a community-driven, organic way, and regardless of the state of evolution of the catchment management structure, the process can be expected to develop through approximately similar stages in an iterative fashion. Sustainability of management, proactive stakeholder participation and public consultation, therefore, needs to form the backbone of all stages of the catchment management process. The relevant stages of the process are similar in nature to those associated with the integrated environmental management (IEM) procedure and include initiation, assessment, planning, implementation, monitoring and review and audit stages (Department of Environmental Affairs and Tourism, 1997). It is important to note that these stages imply a certain degree of chronology, but vast overlaps between the stages are inevitable and, indeed, desirable, to accommodate feedback between tasks and stages. The catchment management process is, by it's very nature continuous, recursive and perpetual.

Within the developments mentioned above, the catchment management plan has a specific role within the ICM process. The plan represents a single, though crucial, step of the wider process and records a vision for the catchment, formalising the understanding of the water, land, social, and aquatic ecology issues or concerns in terms of that vision. The concept of an interest focussed approach will ultimately define how issues or concerns will be addressed through agreed management strategies. In addition, legislative, procedural and technical frameworks for implementation are reflected and as such, legal status is required (Department of Environmental Affairs and Tourism, 1997).

3.8 Review of the Integrated Catchment Management (ICM) approach

The ICM approach is a relatively new concept in water resource management in South Africa and as such an holistic culture including all aspects of the environment is only beginning to develop (van Zyl, 1995). Yet despite the potential problems (Section 3.4) experienced in South Africa and other countries around the world, the implementation of integrated management is conceivable as it takes into consideration and meets the demands of people empowerment, co-operation, participation, partnership, accountability and responsibility, and transparency currently being initiated in South Africa (Brown and van Niekerk, 1995). ICM, therefore, has the ability of becoming a way of life or practice in South Africa, rather than just being seen as a project or task driven action.

Public participation and involvement through public workshops and improved education of the population are important considerations if rivers are to be conserved and their resources managed effectively in the new ICM approach (Forster, 1992; DWAF, 1996; Quibell *et al.*; 1997). The more informed or educated the various water users become with regards to water resource management, the more aspects such as the rights to water abstraction, the discharging of noxious wastes and the unrestricted access to recreational facilities can be understood and the responsibility of the real cost of the water user's activities and actions reiterated (Welcomme, 1992; Tyson, 1995).

In South Africa, the principles of the ideal ICM have achieved widespread support, but actual implementation is still in its infancy. As a result, the new Water Act requires the creation of statutory space for catchment management that, by implication, would reside on or near the foregoing second level of integration of water management (Section 3.2). The striving for increased integration of water management is, therefore, an important aspect of the new Water Act reflected both in the new Water Act Principles, as well as in the evolving national environmental policy formulation process (known as CONNEPP) and in many current initiatives regarding integrated pollution control, solid waste management and strategic environmental assessments.

3.9 Policy frameworks and principles

A properly developed policy framework is a key element in the management of water resources (Larsen *et al.*, 1997). A number of possible elements for such policies have been identified, especially during the preparation of 'Agenda 21' as well as during various follow up activities such as the Copenhagen Informal Consultation (CIC) in 1991 and the International Conference on Water and the Environment (ICWE) in Dublin in 1992 (Larsen and Ipsen, 1997). Policy statements involving water management can generally be found within the legislative framework of most countries. These statements, however, are often shrouded in official acts of government, regulations, action and master plans. In addition, government statutes and constitutional documents often include paragraphs about environmental policies (Enderlein, 1995). Such statements are rarely congruous, and inconsistencies with other policies often exist because they have been developed separately and with different purposes (Warford, 1994).

In order for the adopted political intentions to result in real impacts on the practical management of water resources, it is important that policy statements are clearly defined in proper policy documents. As such, water resource control policy statements can be placed either within a water resource policy document or within an environmental policy document. Other recommendations suggest that the statements form a document in themselves, thereby referring to the overall health-water and resources-environment policies (Larsen *et al.*, 1997). The approach selected depends on the administrative organisation of water resources and environmental management within a particular country.

General principles to be considered within the environmental policy making process include (Larsen *et al.*, 1997):-

- the water resource control policy should be seen as part of a coherent policy framework ranging from overall statements such as can be found in government statutes and constitutions, to specific policy statements defined for environment and water resources management as well as for particular sector development.
- the policy making process should, therefore, include consultations and consensus with all line ministries involved in water resources management, including organisations responsible for overall economic development policies. In addition, when formulating new development policies for other sectors, water resource policy statements should be taken into account where appropriate.
- policy statements must be realistic and should not include statements that cannot be applied in practice, therefore, become meaningless in the context of an operational policy.
- the statements in a policy document need to be relatively long-lived because they must pass an arduous political adaptation process. Detailed guidelines, which may need regular adaptation to the country's actual development level, should thus be avoided and placed rather into the more dynamic parts of the legislation system, such as the regulation framework, that can be amended at short notice.

The guiding principles of the policy document put the political intentions into more practical terms by setting a more detailed conceptual framework that supports the overall policy objectives. It is recommended that these principles should be clarified by a short narrative interpretation. The following guiding principles provide a suitable basis for sound management of water resources and water pollution (UNECE, 1993).

- ❑ Prevent pollution rather than treating the symptoms of pollution - remedial actions to clean up polluted sites and water bodies are generally more expensive than applying measures to prevent pollution from occurring
- ❑ Use the precautionary principle - prevent the application and discharge of hazardous substances into the aquatic environment
- ❑ Apply the polluter-pays-principle - whereby the costs of pollution prevention, control and reduction measures are borne by the polluter (Warford, 1994)
- ❑ Apply realistic standards and regulations - that are achievable and the regulations enforceable
- ❑ Balance economic and regulatory instruments to control water pollution (Bartone *et al.*, 1994)
- ❑ Apply water resource management at the lowest appropriate level at which significant impacts are experienced, be it local, national or international
- ❑ Establish mechanisms for cross-sectoral integration - to ensure the co-ordination of water pollution control efforts within water-related sectors, such as health and agriculture, formal mechanisms and means of co-operation and information exchange need to be established. Such mechanisms should:
  - allow decision makers from different sectors to influence water pollution policy;
  - urge them to put forward ideas and plans from their own sector with impacts on water quality; and
  - allow them to comment on ideas and plans put forward by other sectors
- ❑ Encourage participatory approach with involvement of all relevant stakeholders raising awareness of the importance of water resource control among policy-makers and the general public.
- ❑ Give open access to information on water pollution - the principle is directly related to the principle of involvement of the general public in the decision-making process, because a precondition for participation is free access to information held by public authorities. Open access to information helps to stimulate understanding, discussions and suggestions for solutions of water quality problems.
- ❑ Promote international co-operation on water pollution control - trans-boundary water pollution, typically encountered in large rivers, requires international co-operation and co-ordination of

efforts in order to be effective. Lack of recognition of this fact may lead to wasteful investments in pollution load reductions in one country if, due to a lack of co-operation, measures are introduced upstream that have counteractive effects (UNECE, 1994).

Policy framework formulation for water resource controls needs to be undertaken with due consideration to the previously mentioned guiding principles, as well as to other principles for water resource management laid down in various documents (e.g. Agenda 21) (DWAF, 2000). At policy level the strategy must provide general directions for water quality managers to realise the objectives and the methods to translate the guiding principles into practical management.

3.10 South Africa's approach to policy and principle

Since 1994, many new acts have been promulgated as a result of the Bill of Rights in the South African Constitution. Applicable sections in the constitution of South Africa (Act No.108 of 1996) include:

- Section 24(a) - provides everyone the right to an environment that is not harmful to a persons health and well being.
- Section 24(b) - provides everyone the right to have the environment protected through reasonable legislation and other measures that prevent pollution and ecological degradation; promote conservation; and secure ecologically sustained development and use of natural resources while promoting justifiable economic and social development.
- Section 25 - provides for property rights and the right to a healthy environment.
- Section 32 - provides the right to access information as the lack of information is one of the major obstacles in environmental impact management.
- Section 38 - provides any member of the public the right to get involved (*locus standii*).

Based on frameworks established by the Constitution, various bills and acts have been passed that concern the state of the environment. Within the realms of water resource management, the most important of these is the new Water Act, which recognises that sustainability and equity are the central guiding principles in the protection, use, development, conservation, management and control of water resources (DWAF, 2000).

Close collaboration and cooperation between the DWAF and provincial governments are important. Provincial Water Liaison Committees were established to ensure effective formal communication and liaison between the DWAF and the provincial governments. In addition, the Minister of DWAF was empowered to established statutory Local Water Committees (LWC's). These LWC's undertook the task of local water and sanitation provision until effective local government structures could be established (DWAF, 1996).

In addition to the DWAF, several other government departments controlled issues which impact both directly and indirectly on water resource management. For example, the Department of Agriculture was responsible for agricultural activities and soil conservation, the DWAF the custodian of water quantity and water quality issues, and the Department of Environmental Affairs and Tourism controlled conservation-related issues. Clearly, each of these areas of responsibility influences the temporal and spacial availability and quality of water within a river system. The need to manage these issues cooperatively is further complicated by the fact that different government departments have delegated different levels of management responsibility to provincial and local government levels (DWAF, 1996).

3.11 The new Water Act

Many of the issues raised in the previous paragraphs are addressed in the new Water Act, Act No. 36 of 1998, which repealed the old Water Act (Act No. 54 of 1956). The new Water Act recognises that water is a precious national resource that belongs to all people and acknowledges the government's responsibility and authority over the resource in an integrated manner. Statements and beliefs such as these are quintessential in directing current research and future development.

In terms of catchment management strategies, every catchment management agency (CMA) is responsible for the water resources within its water area and as such, the catchment management strategies must be in harmony with the national water resource strategy. Co-operation and agreement on water related issues from the various stakeholders and interested and affected parties are an important process in the development of this strategy and must continually be reviewed and addressed. The CMA board will be constituted in such a way that the interests of the various stakeholders are represented or reflected in a balanced manner, and the necessary expertise to operate effectively is provided. Additional powers and duties may be assigned or delegated to agencies to establish water use rules and management systems.

Statutory prescriptions should thus direct the establishment of management processes in all catchments that would ultimately lead to full CMAs. Statutory prescriptions should regulate the composition of CMAs to allow for appropriate stakeholder participation. The units of management should coincide with natural catchment boundaries. Statutory criteria should determine the level on which water management functions are assigned to CMAs. Existing statutory institutions should not be transformed to CMAs, but these agencies ought to be established afresh.

3.12 Chapter summary

In following the current trend of a more holistic approach to environmental management, Chapter Three outlines the integrated management approach. The holistic approach to water management whereby naturally occurring water can only be effectively and efficiently managed within a river basin or catchment area, is discussed and the term integrated catchment management defined. ICM is a systems approach to the management of natural resources within the confines of a geographical unit or catchment. The advantage of such an approach is based on the ability to segment the river system into pragmatic management units which can then be sectioned together to create a comprehensive management plan for a river basin. However, this is a very theoretical and relatively new concept in South Africa. A review of current international approaches to ICM, its historical development in South Africa and growing sustainable catchment management structures are identified. South Africa is in the unique situation in that the insight and knowledge gained from international experiences of ICM can be implemented in the South African context. In South Africa, the principles of ICM have achieved widespread support, but actual implementation is still in its infancy. As a result, the legal frameworks and principles of water management and policy is crucial. The importance of the policies and principles is highlighted and discussed in an attempt to strive towards an increased understanding of the integration of water management in South Africa.

Effective environmental decision making involves being well informed about relevant and appropriate information on which to base various choices. The need for effective environmental management within the integrated catchment management approach leads to the discussion of decision support systems and in Chapter Four.

CHAPTER FOUR

4. DECISION SUPPORT SYSTEMS: THEORETICAL FRAMEWORK AND TOOLS AVAILABLE FOR ENVIRONMENTAL DECISION SUPPORT SYSTEMS

4.1 Introduction

The lack of a comprehensive review of DSS in South Africa is discussed in this chapter. Before implementation of a DSS can be undertaken, an understanding of the historical development of DSS is necessary. A review of the development of DSS and knowledge obtained from past experiences, can contribute positively as a basis for the development of a new EDSS while averting potential mistakes. The historical developments of DSSs are reviewed in Section 4.1 to Section 4.10. Thereafter, the components and tools available for EDSS will be discussed.

Although EDSS are a relatively new concept and approach in the environmental field in South Africa, computer-based decision making systems have been available in the United States of America and Europe since the early 1960's (Keen and Scott Morton, 1978; Alter, 1980). Data orientated information systems of the 1950's and the 1960's gave way to more model-orientated information systems in the 1970's and the 1980's (Scott Morton, 1971). The systems became more data integrated, more comprehensive in scope and varied widely in the extent to which systems outputs affect actual decisions (House, 1983). Effective decision making involves being well informed about relevant and appropriate information on which to base various choices (Sauter, 1997). Such information includes historical data collected over time and specialised research information. Both forms constitute facts, numbers, impressions, graphics, pictures and sounds which are collected from various sources, joined together and organised in such a way as to facilitate in the understanding of the problem and the various options available (Sprague and Carlson, 1982).

The procedures of organising and examining the information involve models created to facilitate decision makers in understanding the ramifications of a selected option. Models can range from quite informal representations to complex mathematical relationships (Adriaanse and Linggaard-Jørgensen, 1997; Sauter, 1997). Data are a prerequisite in the determination of the quality of the decision which in turn is dependant on the adequacy of the available information, the quality of the information, the number of options and the appropriateness of the modelling effort available at the time of the decision (McLeod, 1995). While it is not true that the more information, the better, it is true the more appropriate the data the better. In fact, to improve the choice process, the information collection and analysis processes need to be improved (Sauter, 1997). To this end, DSSs can be used to bring together information from a variety of sources, assist in the organisation and analysis of information, and facilitate the evaluation of assumptions underlying the use of specific models (Jelassi *et al.*, 1992; LaPlante, 1993; McLeod, 1995; Adriaanse and Linggaard-Jørgensen, 1997; Sauter, 1997).

Access to information empowers the decision maker to analyse the information in a manner that will be helpful to a particular decision and provide interactive support (McLeod, 1995). This will provide the opportunity to improve data collection and analysis processes associated with decision making. In addition, the opportunity to improve the quality and responsiveness of decision making and hence the opportunity to improve the management of institutions, forums or corporations (Sauter, 1997) is provided.

The origins of the first DSS were founded in the business sectors, brought about by the increasingly practical nature and rapid changes in computer technology (low-cost access to models, systems and databases through the use of interactive terminals) (Alter, 1975; Bonczek *et al.*, 1981; Sprague and Watson, 1983). As such, early definitions of DSS represent the role of the computer in the management decision-making process (Keen and Scott Morton, 1978), and imply the use of computers to assist and support managers in their decision process in semi-structured tasks, thereby improving the effectiveness of decision making rather than its efficiency. The decision making process is thus made up of two distinct, often conflicting facets, namely, efficiency (the performance of a given task as well as possibly to some predefined performance criterion) and effectiveness (the identification of what should be done while assuring that the chosen criterion is relevant). Conflict arises in that effectiveness requires adaptation and learning while efficiency involves a form of in-house maintenance (Keen and Scott Morton, 1978).

The philosophies of DSS are closely aligned and hold similar views to management information systems and the broad field of operations research or management science. However, the DSS concept is unique in its area of impact and payoff to the organisation and its relevance for managers. In this paradigm, DSSs can be viewed as a natural evolution in computer applications which defines a strategy for integrating the analytical power and data processing capabilities of the computer with the managers problem solving processes and needs (Lawrence and Lorsch, 1967; Alter, 1975; Keen and Scott Morton, 1978).

4.2 What is a decision support system?

A DSS is defined as an interactive computer-based system that supports choice by identifying and solving problems; assisting the decision maker in organised information and modelling outcomes or decisions (Alter, 1975; Sauter, 1997; Power, 2001).

Between the extremes of management information and expert systems (Dickson and Powers, 1973), lies the area of the DSS which is intended to help decision makers identify and access useful information in processing poorly structured, under-specified problems (Laudon and Laudon, 2000). In addition, flexible mechanisms for data retrieval, flexible mechanisms for data analysis, and tools that help understand problems, opportunities and possible solutions are provided (Sauter, 1997). The DSS helps in the generation of alternatives and 'what if' analyses to determine the benefit of the result in comparison to the assumption made. Prompting users to consider sensitivity analyses or at least provide suggestions on how to improve analyses of the problem and information available (Sauter, 1997). The position of DSSs in relation to organisational level and type of decision is illustrated in Figure 4.1.

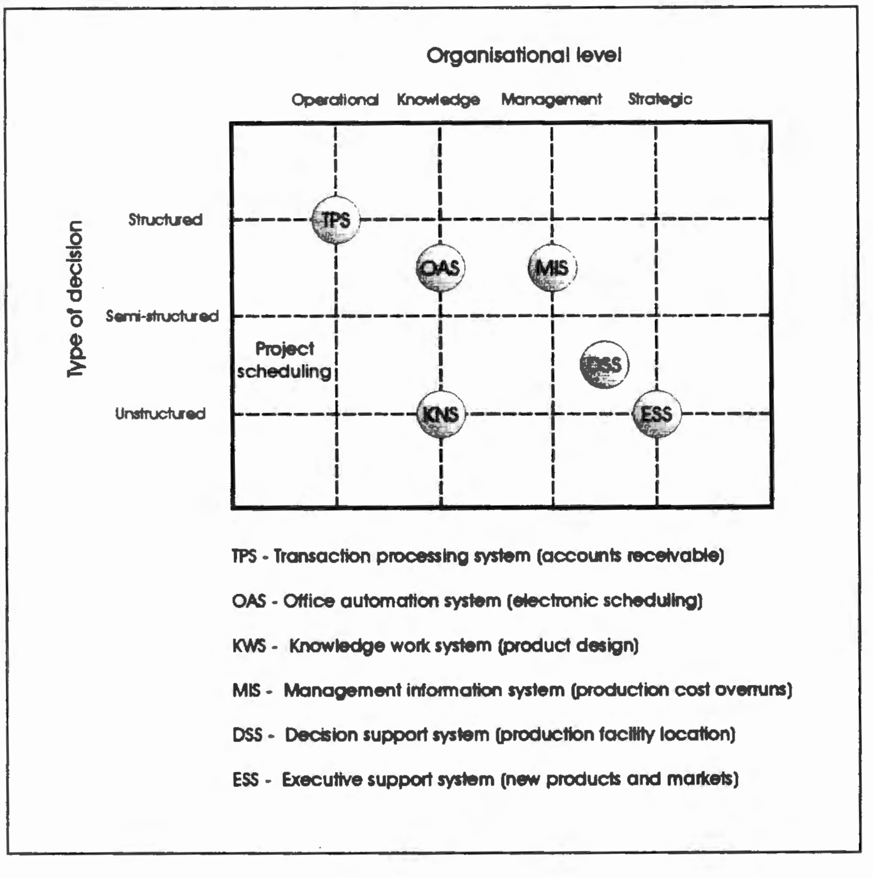

Figure 4.1: Position of the decision support system in relation to type of decision and organisational level (modified after Gorry and Scott Morton, 1971; Laudon and Laudon, 2000)

4.3 Historical foundations of Decision Support Systems

The perspectives and origins of DSSs are derived from seven broad categories. These categories, namely, computer science, information economics, management science, behavioural science, data processing professionals, management and DSSs are paramount in the understanding of the historical developments of DSSs (Alter, 1975; Keen and Scott Morton, 1978; Baxter, 1983; Geoffrion and Powers, 1983; Blanning and King, 1992).

DSSs are a service tool which focus the attention on building a system in relation to key decisions and tasks, with the specific aim of improving the effectiveness of the manager's problem solving process (Alter, 1976; Keen and Scott Morton, 1978; Sprague and Watson, 1983). In this way, the level and attention of operations is shifted towards the issues of managerial problem solving. It is important to note that DSSs do not replace the role of the manager, but rather support and enhance the manager's decision making ability through an interactive computer system with access to analytical powers, models and databases. Due to the interactive nature of the system, it is vital that continual growth and evolution occur as the level and ability of the user adapts, learns and advances (Geoffrion and Powers, 1983). Responsible managers are then able to cultivate a more complex DSS from a simple and well-defined base (Keen and Scott Morton, 1978).

4.4 The acceptance of Decision Support Systems

Four factors contribute to the acceptance as to why DSS technology is now becoming important in the choice process of environmental issues. The first is that desktop computing has made technology more accessible and easier to use (McLeod, 1995). Historically, computing was confined to interaction with a mainframe in a batch mode from a fixed terminal located in a general office or laboratory. As a result response time was often slow and not conducive to helping the decision maker. In contrast, decision makers using desktop computers and laptop technology can download and analyse data almost anywhere and at a convenient time for the decision maker (Sauter, 1997). The second factor contributing to the acceptance of computer-based systems is the development of more user-friendly computer software packages. There is no longer the need to know a computer language in order to access data on the computer. Instead, data are easily imported into spreadsheet packages that facilitate the determination of trends, graphs and interrelationships. This user-friendliness is a feature that users have come to expect and as such has directed the development of software to include ease of use and a greater reliance on online help options and context-sensitive help (McLeod, 1995). Another factor contributing to the acceptance of the DSS which follows on from the way in which software is written is that most high level managers are exposed to computers on a day-to-day basis and are thus less likely to fear their contribution in the decision making process. Although the three factors all contribute significantly to the acceptance of technology in the decision making process, it is the cost of not using the technology that is becoming too high, thus pushing the decision makers into using the DSS technology currently available. Such high costs include accountability for decisions and legalities of actions and mitigation undertaken (Sauter, 1997).

4.5 Decision Support Systems and the decision making process

4.5.1 A systems approach to decision making

Problem solving or decision making arises out of a need to meet some predetermined objectives. A systematic approach to problem solving known as the systems approach consists of three types of effort namely preparation, definition and solution (McLeod, 1995). Unique factors such as different styles of problem sensing (McKenny and Keen, 1974), information gathering and information using can influence problem solving (Robey and Taggert, 1982). In the course of solving a problem, many decisions will be made. A decision is defined as a selection of a strategy or action. Decision making is, therefore, the act of selecting the strategy or action that the manager believes will offer the best solution to the problem. Usually there are several strategies or actions that can be considered. Identification of decision alternatives is one of the keys to problem solving (McLeod, 1995).

For decision making to occur, two elements must be present namely, a problem and a problem solver (Kleindorfer *et al.*, 1993). Other elements are less obvious, but if absent, the end results are likely to be poor. The solution to a problem must best enable the system to meet its objectives, as reflected in the performance standards. In addition, the problem solver must have available information that describes the current state. If the current state and the desired state are the same, there is no problem and the manager need take no action. If these two states are different, some problem is the cause and must be solved. The difference between the current state and the desired state represents the solution criterion. It is the problem solver's responsibility to identify alternative solutions. This is one step of the problem solving process where computers have been of little help. The problem solver typically relies on experience, or help from the non-computer portion of the information system such as input from others both inside and outside the organisation (Vazonyi, 1978). Once alternatives have been identified, the information system can be used to evaluate each one. This evaluation should consider any possible constraints, which can be either internal or environmental. Internal constraints take the form of limited resources. Environmental constraints take the form of pressures from various environmental elements, such as the government or competitors, to act in a particular way. When all of these elements exist and the manager understands them, a solution to the problem is possible.

Once procedures have been devised, computers can solve structured problems without the need for manager involvement. On the other hand, the manager has to do the work in solving unstructured problems. In the vast middle ground of semi-structured problems, the manager and the computer can jointly work towards a solution. The recommended framework for using the computer became known as the systems approach - a series of problem solving steps that ensure the problem is first understood, alternative solutions are considered and the selected solution employed.

Although the many descriptions of the systems approach all follow the same basic pattern, the number of steps can vary. Preparation equips the manager for problem solving by providing a systems orientation (Flood and Jackson, 1991). Definition effort consists of identifying a problem to be solved and then understanding it. Solution effort involves identifying alternative solutions, evaluating them, selecting the one that appears best, implementing that solution and following up to ensure that the problem is solved (Cornell, 1980).

Table 4.1: System orientation phases and steps for effective decision making (Cornell, 1980; Flood and Jackson, 1991)

Phase	Step	Approach
Preparation effort	View the organisation as a system	• see your organisation as a system • accomplished with the use of the general systems model • see how the organisation fits the model
	Recognise the environmental system	• the organisation's relationship to the environment is important • eight environmental factors
	Identify the organisations sub-systems	• identify the major sub-systems of the organisation such as functional areas • regard the levels of management as sub-systems - here the sub-systems have a superior-subordinate relationship and are connected by both information and decision flows; information flow is important both up and down the management scale • resource flows as a basis for dividing up the organisation into sub-systems
Definition effort	Proceed from a system to a sub-system	• determine if the subsystems integrate into a smoothly functioning unit and are they working toward the systems objectives

	Analyse system parts in a certain sequence	• evaluate standards which need to be valid, realistic, understandable and measurable • compare system outputs with standards • evaluate management • evaluate the information processor • evaluate the inputs and the inputs resources • evaluate the transformation process • evaluate the output resources
Solution effort	Identify alternative solutions	• identify different ways to solve the same problem through brainstorming or joint application design which is a group decision support system approach to problem solution.
	Evaluate the alternative solutions	• evaluate using the same evaluation criteria both advantages and disadvantages
	Select the best solution	• Mintzberg (1976) identified three ways to select the best alternative - analysis - evaluation of options - judgement - mental process of a single manager - bargaining - negotiations between several managers
	Implement the solution	• the problem is not solved purely be selecting the best solution • it is still necessary to implement the solution
	Follow up to ensure that the solution is effective	• stay on top of the situation to make certain that the solution achieves the planned performance

The steps of the systems approach provide a good way to categorise the multiple decisions that must be made in the process of solving a single problem. The computer-based information system can be used as a support system while applying the systems approach. A computer-based information system, such as a DSS, expert system or office automation application can provide support to a separate decision. It is also possible for a computer-based information system to support several decisions. The systems approach serves as a bridge between the problem and the computer-based information system, providing a framework for the various decisions.

Personal factors also influence problem solving. Each manager has a unique problem solving style and their style influences how they engage in problem sensing, information gathering and information using (McKenney and Keen, 1974; Szilagyi, 1981). Managers fall into different basic categories in terms of their problem-sensing styles or how they confront problems. Differences in how managers develop and evaluate alternatives once problems arise can also influence the problem solving process (Kleindorfer *et al.*, 1993). Managers can exhibit either a perspective information gathering style, or a receptive information gathering style. In the same vein, managers tend to favour a systematic or intuitive style for using information to solve problems.

In designing a computer-based system, it is important to recognise these individual differences. The critical element in the computer-based information system is the manager, and each manager uses the system in a different way. However, managers seldom attempt to solve problems alone. Group problem solving has come to the fore, but, within groups, personal differences exert a strong influence.

Unlike the management information system which is tailored to the information needs of large numbers of managers, the information is not adequate for making specific decisions to solve specific problems (Dickson and Powers, 1973). The DSS was conceived as a way to meet this need as it provides both problem-solving information and communications capability in solving semi-structured problems (Sprague and Watson, 1983). The information is produced in the form of periodic and special reports, and outputs from mathematical models and expert systems. The communication of which are used when groups of managers engage in problem solving.

4.5.2 A Decision Support Systems approach

The DSS concept began in the late 1960's with computer timesharing. For the first time, a person could interact directly with the computer without having to go through information specialists. It was not until 1971, however, that the term DSS was coined by Gorry and Scott Morton (1971). They felt a need for a framework to channel computer applications towards management decision making and developed what has become known as the Gorry and Scott Morton grid. The grid is based on Simon's (1975) concept of programmed and non-programmed decisions and management levels.

From the beginning of the DSS era, mathematical modelling has been recognised as an integral component. Modelling provides the manager with some real advantages, but there are disadvantages as well. The disadvantages of modelling are discussed in greater detail in Section 4.11.6. The most recent embellishment of the DSSs concept is the group decision support system. The group decision support system endeavours to improve communications among group members by providing stimulating environments.

According to Simon (1977), decisions exist on a continuum, with programmed decisions at one end and non-programmed decisions at the other. Programmed decisions are repetitive and routine to the extent that a procedure has been worked out for handling them. Thus they do not have to be treated *de nova* (as new) each time they occur. Non-programmed decisions are novel, unstructured and unusually consequential. No determined method for handling the problem exists as it has not arisen before, either because of its precise nature which is complex, or because it is so important that it deserves a custom tailored treatment.

Simon (1977) also identified four phases that a manager goes through when solving a problem, namely:

- intelligence activity - searching the environment for conditions calling for a solution
- design activity - inventing, developing and analysing possible courses of action
- choice activity - selecting a particular course of action from those available
- review activity - assessing past choices

Simon's (1977) four phases relate directly to the steps of the systems approach. Simon's phases are, therefore, an interpretation of the systems approach. Managers follow these patterns in either a specific or a general way when they solve problems. Information specialists also follow these patterns when they engage in systems development.

Alter (1976) building on Gorry and Scott Morton's (1971) framework, conducted a study of 56 DSSs. The study enabled a taxonomy of six DSS types based on the degree of problem solving support. The type that offers the least support is the one that enables the manager to retrieve information elements. Slightly more support is provided by a DSS that permits the manager to analyse entire files such as the database for a special report that uses data from the inventory file. Still more support is provided by systems that prepare reports from multiple files. The first three DSS types provide support in the form of special reports and response to database queries and periodic reports.

The final three DSS types involve the use of mathematical models. A DSS that allows the manager to view the results of various decisions is a model that can estimate decision consequences. The model is unable to determine the best option, only what might happen if such a decision were made. These models also allow the user to assign subjective probabilities such as a risk analysis model that uses estimated probability distributions for each of the key factors. The Alter (1976) study is important for two reasons. First, it supported the concept of developing systems to address particular decisions. Second, it made clear that a DSS need not be restricted to the more exotic approaches of database querying and decision modelling but could include periodic reporting.

According to Keen (1991) the objectives that a DSS should achieve are to assist and support managers in order to improve the effectiveness of decision-making. These objectives correlate with the three, fundamental principles of the DSS approach namely problem structure, decision support and decision effectiveness. DSS characteristics include (Sauter, 1997):

- the ability to access data from a variety of different sources;
- the development and evaluation of a model of the choice process - thereby allowing the users to transform the data via models into information that can help make good decisions; and
- providing a good user interface through which users can easily navigate and interact

In this way, assistance is given to the manager to use their best judgement in determining when a decision will contribute to a problem solution.

4.6 The models of decision making

The guiding principle of decision making is that different decision makers will need quite different information to support their choice processes. Similarly, a decision maker will need different support when facing different choices in different choice environments. Good DSS designers need to be aware of these needs and respond to them in order to provide decision makers with the flexibility to change the emphasis they place on various criteria (Sauter, 1997). Literature pertaining to the models and processes of decision making are extensive and can be divided broadly into four schools of thought (Keen and Scott Morton, 1978). These views are listed below and concisely reviewed:

- the rational view - claims that decision makers are all-knowing and able to evaluate all alternatives (Sauter, 1997). This view is considered to be the classical normative theory of decision making whereby any solution but the best, is dissatisfying (Keen and Scott Morton, 1978). Implementation requires technical competence and the education of those involved to adopt the rational perspective which is explicit and consistent in its assessment (Sauter, 1997). Although impractical and idealised, the rational paradigm still remains a dominant influence (Keen and Scott Morton, 1978). The rational view incorporates six forms of rationality associated with a reasonable decision process, namely, economic, technical, legal, social, procedural and political (Sauter, 1997). In the decision making process, decision makers consider these six facets of rationality either consciously or sub-consciously. As such, the designer needs to ensure that all the aspects of rationality are provided for in the decision making process to facilitate in the choice process. It is important to note, however, that not all systems will contain information regarding all forms of rationality equally (Sauter, 1997).

- the process orientated view - considers decision makers to be intentionally rational although cognitive limits lead to 'bounded rationality' (Keen and Scott Morton, 1978). Simon (1975), highlights the constraints imposed by bounded rationality, by placing emphasis on heuristic rules of thumb and searching for solutions that are good enough (satisficing). One manner of illustrating the bounded rationality approach to decision making is the theory of 'muddling through' (Lindblom, 1959; Braybrooke and Lindblom, 1970). 'Muddling through' describes the decision makers' unwillingness to make bold changes through choice. Rather, preferring minor decisions that cause only incremental changes in the environment.

The concept of not using all possible information, is not necessarily bad. The problem arises, however, when the choice to use limited information is associated with bias or uninformed decision making. Clearly, the bias (especially if it is unintentional) and the absences of crucial dimensions of an alternative are problems. It is, however, important to ensure that decision makers learn the most they can from the information available through easy integration of information, the effective use of models, and encourage analysis of the sensitivity of the costs and benefits of alternatives to the underlying assumptions (Sauter, 1997).

- The organisational procedures view - focuses on the interrelations among components of the organisation (Keen and Scott Morton, 1978). It highlights and stresses organisational structure, mechanisms for communication and co-ordination, and the standard operating procedures by which decision making is systematised and often simplified. It seeks to understand decisions as the output of standard operating procedures invoked by an organisational sub-unit. The emphasis in design is to discover what these procedures are and how they may be supported and improved. In this way, the importance of identifying organisational roles, channels of communications and relationships are stressed (Keen and Scott Morton, 1978).

- the political view - participation in the decision making process is viewed as actors of a play with roles to render. They have strong individual preferences and vested interests and form coalitions of organisational subgroups. Decisions are frequently dominated by bargaining and conflict, with the result that only small deviations from the status quo are normally possible (Keen and Scott Morton, 1978).

The models of DSS clearly indicate that there is no conclusive manner to review the decision making process and that for a given situation, the 'correct way' may involve a blend of all points of view although in some instances these directly contradict each other. The best way to use or synthesise these very divergent viewpoints is by adopting a diagnostic perspective. Designers need to be sure that they understand the realities of the decision situation and that they have a useful service to offer.

4.7 Uses of a Decision Support System

DSS covers a wide scope of environs ranging from strategic planning to operations management; and exist in both the public or government sectors as well as the private (profit and non-profit) sectors. Due to the wide range of applications, it is often difficult to assess when the use of a DSS is appropriate and most beneficial. Sauter (1997) imparts that DSS are most useful when it is not obvious what information needs to be provided, what models to be used, or even what criteria are most appropriate. In other words, DSS are most useful when it is not obvious how the choice should be made. Furthermore, since DSS proceed with requests from decision makers in the order and manner selected by the user (and not necessarily linear in their application), they tend to be associated with situations in which users proceed differently with each problem (Meador *et al.*, 1984). That does not mean, however, that a DSS cannot be useful for a more structured problem (Sauter, 1997). The development of DSS to obtain accurate information are highlighted by Hogue and Watson (1983).

4.8 A framework for the analysis of Decision Support Systems

Before building a DSS, it is essential to identify both the normative decision process that the system is intended to generate as well as the actual decision process that exists (Keen and Scott Morton, 1978). The decision-centred approach requires careful analysis of the decision situation from all points of view. This approach may be summarised as starting from a descriptive analysis of the existing decision processes and defining a normative model as the basis for system design. Improving decision making requires supporting managers and helping them adapt, learn and move towards the prescriptive position. If the system does not start from this perspective, then the managers may be both unwilling and unable to change and implement a DSS (Keen and Scott Morton, 1978).

The framework for a successful decision support involves three aspects, namely: strategic planning, management control and operational control (Scott, 1995). The strategic planning avenue of decision support involves the process of deciding on objectives for the organisation, changes in these objectives, on the resources used to obtain these objectives, and on the politics that are to govern acquisition use and disposition of resources (Sprague, 1980). Defining these objectives is difficult and implies an emphasis on reviewing the organisations' environment. The strategic planning process typically involves senior managers and analysts and often requires innovation and creativity. The complexity of the problems that arise and the non-routine manner in which they are handled makes it difficult to appraise the quality of the planning process and to define appropriate rules (Keen and Scott Morton, 1978).

The final aspect of successful decision support, namely operational control, involves the process of assuring that specific tasks are effectively and efficiently carried out. Operational control is primarily concerned with performing predefined activities, whereas management control more often relates to the organisation's policies (Srinivasan, 1985). Less judgement is required in the operational control area due to the fact that the tasks, goals and resources have already been carefully defined in the strategic planning and management control aspects (Keen and Scott Morton, 1978).

Although the boundaries of each of these three types of decisions are often not clear and tend rather to overlap each other to form a continuum, the definitions are still useful for analysing the information systems needs and activities. This is due to the fact that the information requirements of each of these three categories are different. The difference being not simply one of aggregation, but reflecting the characteristics of the information required by managers. Table 4.2 tabulates the role of structured, semi-structured and unstructured decisions and the information characteristics in each category.

Table 4.2: Information characteristics of strategic planning, management control and operation control areas of decision making

Task variables	Strategic planning	Management control	Operational control
Accuracy	Low	←——→	High
Level of detail	Aggregate	←——→	Detailed
Time horizon	Future	←——→	Present
Frequency of use	Infrequent	←——→	Frequent
Source	External	←——→	Internal
Scope of information	Wide	←——→	Narrow
Type of information	Qualitative	←——→	Quantitative
Age of information	Older	←——→	Current

Each of the variables in the table has different characteristics in the three stages of the continuum. Under these conditions, the true worth and value of the DSS are most effective as the manager and the system can provide a more effective solution than either one alone. Unstructured decisions are decisions that are either incapable of being structured or that has as yet not been examined and as a result remain unstructured (Keen and Scott Morton, 1978). In such cases human intuition plays an important role in reaching a conclusion.

DSSs, therefore, provide a variety of levels of support, the exact choice of which can only be determined from the decision analysis. The most primitive support provides access to facts or information retrieval, the second level of support involves the addition of filters and pattern recognition ability to this data retrieval. This process provides managers with the ability to selectively ask for information and to give conceptual meaning to the data and may benefit from routines that provide graphical summaries or time series analysis. The third level adds more generous computational facilities to the first two and permits the managers to ask for simple computations, comparisons and projections. The final level of support provides useful models to the manager. The characteristics of usefulness are important because the model must be designed to provide the managers with answers they can and will act on(Keen and Scott Morton, 1978). Accordingly, it may be very simple and crude rather than mathematically sophisticated and will often be based on heuristic rules and standard procedures for analysts.

4.9 Appropriate data support

DSS need appropriate data support to provide a range of information without overwhelming the decision maker (Sauter, 1997). Information processing requires the decision maker to perceive and process information, recognise patterns in the information and remember past events to understand information currently available (Adriaanse and Linggaard-Jørgensen, 1997). The ultimate goal of the DSS is to help separate crucial information from the irrelevant information, and to understand it better. To this end, decision makers need to acquire information from the DSS in a meaningful fashion. Filtering is a crucial component because of the huge number of stimuli operational and is done to remove information believed to be irrelevant to the task under consideration.

The manner in which decision makers screen information with regards to a task is well known (Sauter, 1997) and is strongly influenced by experience. Models of information process indicate that people develop in their information processing needs as a function of their maturation, experience, education and self-regulation. Rasmussen (1983) identifies experience as an important predictor of the information needs of decision makers. In particular, he notes that decision makers are guided by past experiences and the success of that past experience. Thus, positive outcomes resulting from the choice process are reiterated, irrelevant of the approaches and techniques. Rasmussen (1983) believes these decision makers follow a data-driven approach to choices, deliberating the characteristics of an alternative and compare those to something they know and understand.

Awareness of the different decision making styles is important to ensure that the different approaches are incorporated into the DSS. Rasmussen (1983) suggests that the complete reliance on quantitative models does not adequately reflect the requirements of many decision makers. Rather, qualitative systems would offer support for the user at any of the more advanced behaviour levels. Such systems would be especially useful at the knowledge-based level, where information must be used in unfamiliar ways and where there are not pre-established, quantitative rules for processing data. Qualitative measures should guide the overall analysis, while quantitative models can be used for more detailed analyses of the system.

Klein (1980) also developed a model of decision making based on the experience of the decision maker. While many of the ideas are parallel to those expressed by Rasmussen (1983), Klein (1980) adds a description of experts and their decision making process. A more practical use of Klein's (1980)s model is in helping decision makers see how the current choice context is similar to one previously faced. Another model, proposed by Dreyfus and Dreyfus (1986), describes six levels of expertise in decision making through which decision makers progress as they become more experienced in their decision making. Along the way, they change the kind of information they seek and the manner in which they expect to have the information represented.

But what does this entail for the decision support system?

The most obvious conclusion is that decision makers develop and begin to follow a less regimented process. A novice decision maker will need a greater deal of structure in their system, while a master decision maker will need a greater deal of flexibility. Not only does this structure/flexibility criterion apply to the users movements through the system and to the users interface, but it also refers to the modelling procedures and requirements. While warning messages and suggestion boxes would be well received by novices, they will actually weaken the decision making behaviour of those at the expertise and mastery levels (Sauter, 1997).

Similarly, novice and advanced beginner decision makers will need help in monitoring the quality of their decision processes. This means they need guidance and supervision of their selection of data and models during the choice process. In addition, they will improve their performance if, over time, the outcomes of their choices are monitored and relayed back to them. In this way, they can determine what has worked well and what has worked poorly (Sauter, 1997).

Not only do the type and amount of structure and of decision making aids change with experience, but the actual information preferred by decision makers changes. Sauter (1985) and Sauter and Schofer (1988) found that novice decision makers prefer very explicit, quantitative data regarding the resources available. As they gain more experience, they move from seeking feasibility information to seeking information about the performance of alternatives under consideration. The results suggest that the database and model support required by decision makers will shift over time. Hence, the system must have the flexibility to change with the decision maker and accommodate changes in both the information sought and the models employed (Sauter, 1997).

4.10 Group decision making

Understanding the decision making processes is difficult because of the variability between individuals in terms of the phases they adopt, the methods they employ and the data that are important to them (Bui, 1987; Thierauf, 1989; Bostrom *et al.*, 1992; Jessup and Valacich, 1993; Coleman and Khanna, 1995). However, the variability increases immensely when groups make decision, thereby making the support of a group decision making activity that much more difficult.

Group decision making systems are an interactive computer-based system to facilitate the solution of unstructured problems by a set of decision makers working together as a group (de Sanctis and Gallupe, 1987; Kraemer and King, 1988). In theory, groups are developed to address a task because they can provide better solutions than an individual. Through discussions, groups can develop a better understanding of the complexity of a problem. Furthermore, since groups have more skills and understanding than any individual, they can generate more alternatives for problem solving. Similarly, since there are many individuals involved, there is a greater chance that errors may be found early. Finally, if a group participates in a decision, the members are more likely to accept the decision and hence not resist the outcome of the process (Sauter, 1997).

However, group decision making does not always occur in the manner anticipated. There are two major problems associated with group work. First there is the tendency to conform to a given solution too early. Social pressure may convince some individuals to accept a solution before they are ready to do so. Similarly social pressure, especially among busy individuals, may lead to an incomplete analysis of the task and incomplete use of information (Kleindorfer *et al.*, 1993). Related to this is the problem of group dynamics. Too often, the person with the highest authority, the person who has been there the longest, the person with the best credentials or the person with the loudest voice or the most dominant personality dominates the discussion and, therefore, the generation of alternatives and resolution of the task. Shy, relatively inexperienced or new individuals have difficulty being heard. This can be a particular problem if they have drastically different views of a problem or skills. Whereas group members should be relying on the substance of the information and the appropriateness of the alternatives to guide them in deciding how pivotal they are to the discussion, they too often view the personality or the group dynamics when deciding the merit of an argument (Grobowski *et al.*,1990).

4.11 Components and tools available for Environmental Decision Support Systems

EDSS comprise four components, namely: the database management system, the model base management system, the user interface and the mail management system.

The database management system's core function is to provide access to the data and the control programs necessary, to transform the data into a form appropriate for analysis, without the user programming the action. In addition, the database management system needs to be sophisticated enough to facilitate the merging of data from different sources, even when, in most cases, the user does not know where they are physically located (Sauter, 1997). This is made up of four components namely: data, information, database and data warehouse components.

The model base management system performs a similar task for the models in the DSS by keeping track of all the possible models that might be run during the analysis, as well as controlling the running of the models. Such control might include the syntax necessary to run the jobs. Additional functions of the model base management system include:

- creating links between models so that the output of one model can become the input into another model;
- providing mechanisms for sensitivity analyses of the model after it is run; and
- the provision of context-sensitive and model-sensitive assistance to help the user question the assumptions of the models to determine if they are appropriate for the decision under construction.

Unlike the roles of the database management system and the model base management system, which are essentially hidden components of the DSS, the user interface and the mail management system components are more apparent and thus appear to play more of an active role in the decision making process due to more frequent interaction. The user interface represents the mechanisms whereby information is input to the system and is output from the system. In addition, the user interface includes all the input screens by which users request data and models, as well as the output screens through which users obtain the results (Davis, 1989). Many users think of the user interface as the real DSS, because that is the part of the system they see and is most apparent (Laudon and Laudon, 2000).

The last component of DSS, namely, the mail management system, is a relatively new component of DSS and its existence as a core component facilitating in the decision making process is still currently under some debate within the literature. The mail management system uses electronic mail as a source of data, modelling or general help in the decision making process (Sauter, 1997).

EDSS, unlike the more traditional DSS, include all the components of conventional DSS as well as specialist tools such as environmental modelling and GIS. In addition, the EDSS must ensure a flexible, multi-functional approach of the various disciplines, with multiple sources and approaches to ensure institutional collaboration (Adriaanse and Linggaard-Jørgensen, 1997). The various components that contributed to the Mooi River Catchment case study to make up an environmental decision support system are discussed further in Sections 4.11.1 to 4.11.9.

4.11.1 The data component

Data are assumed or known facts and figures from which conclusions can be drawn (Sauter, 1997). However, facts and figures are not the only forms of data that might be considered for DSS. Other aspects, such as opinions can be valuable as they enrich decisions developed from more objective data. Similarly, long term environmental plan developments need to gauge the expected changes in regulations, governments and attitudes over an extended period of time. These options are combined together with quantitative models, as the basis of the long-range estimate needs. In each case, opinions and judgements are used as inputs to a choice process, supplementing standard 'objective' data to represent aspects of the choice that would otherwise be lacking. Since DSS are intended to support the choice process, they should accommodate subjective data and opinions, providing efficient ways of searching for and using these data. Other decisions might entail data not stored in conventional ways, for example, pictures, photographs, video or audio data. While the advent of virtual reality technology might advocate 'experiences' before alternatives can be selected. Data in a DSS is thus anything that is fed into models and used by decision makers to evaluate alternative actions (Adriaanse and Linggaard-Jørgensen, 1997). The most important aspect of the data is that it is valuable to the decision maker. Of course, the difficulty for the designer is in determining what will be valuable and/or useful to the decision maker.

Today, different kinds of information are computerised, which present their own set of advantages, disadvantages and new challenges. Advantages include the fact that the data necessary to support decisions is machine readable and processable, and can thus be included into the DSS. However, there is a temptation to computerise everything and let the decision maker sort out what is needed (Sauter, 1997). While this philosophy probably ensures that useful, machine-readable data are incorporated, it also allows for incorporation of more data that are unnecessary to the decision. This can lead to decision makers becoming overwhelmed at the amount of information they need to process. With a large amount of data, they could easily miss data that are relevant to the decision. In addition, the inappropriate use of irrelevant information or the use of irrelevant data in an inappropriate way (Guptill, 1999) become factors. Of most concern, is the fact that they may become discouraged with the system and just not use it. The challenge of DSS today is thus to include all of the necessary machine-readable/processable information in the DSS while excluding the unnecessary data. Thus the importance of including only data that are useful to the decision is ensured (Adriaanse *et al.*, 1996).

4.11.2 The information component

In contrast to data, the term information means acquired knowledge. While subtle, the difference is important in that it represents the difference between a computer application and a DSS. In general, raw facts and figures represent data while processed facts and figures represent information. Processing of information can arise as a result of either numerical or graphical summarisation, or as the output from models (Adriaanse and Linggaard-Jørgensen, 1997).

DSS involve a compromise between the normative view of decision making, the subjective view of what is useful, and the realistic view of whether and how information can really be used in the choice process. Sometimes this means that the data are excluded from the system, while at other times it means that parallel data, more appealing to the decision makers, are included in the system. Compromise also entails adding help screen savers and warning messages to assist decision makers to use the information (McLeod, 1995).

In addition to content, other aspects of the data can determine whether they might be valuable.

Characteristics of information include timeliness, sufficiency, level of detail and aggregation, understandability, freedom from bias, decision relevance, comparability, reliability, redundancy, cost efficiency, quantifiability and appropriateness of data (Sauter, 1997). Appropriateness of each of these categories is defined in terms of the choice context, the decision maker and the decision environment under consideration. It is important to realise that there is no universally correct or universally incorrect value that each of these takes on.

The aggregation level of data is an important factor for determining the usefulness of information in a DSS. Total disaggregation requires the system to provide an easy mechanism by which the decision maker can view the various fields on which data can be aggregated, and an easy method for specifying the aggregation that is appropriate for the required application (Sauter, 1997).

The characteristic of information understandability is important in that if decision makers cannot understand what is in the database, or if the database lends itself to perceptual errors, decision makers cannot use it effectively. The key is to simplify the representation of the database without losing the meaning of the data. One approach is to include an electronic data dictionary which provides an explanation and representation of the fields. Access to the document could be provided through a general search of the dictionary on request or through user-activated context-sensitive help screens (Bigus, 1996).

4.11.3 The database component

Historically, data were kept in files associated with an individual application. Thus, each time something changed with regards the data, the appropriate files associated with each application that used the data also needed to be changed. Update frequency depended on the needs of the DSS, the data maintenance for the original purpose, and the volume of activity. It is clear, however, that this file transfer process is inefficient. Data entry errors are hard to fix across applications, and it is difficult to ensure that all users are accessing the same values. As needs in the various applications change and fields are inserted or deleted, the problem becomes even worse. In addition, since the same data are kept in many places, storage media also need to be duplicated (Sauter, 1997).

As the importance of data as a resource was recognised, so collection and maintenance processes improved. One of the most significant advances was the creation of databases which are collections of interrelated data (Veregin, 1999). The goal of the database concept is to store related data

together, in a format independent of the DSS. Since data storage and data use are independent, decisions regarding storage are made independently of decisions regarding usage. People who maintain the data can focus on minimising redundancy in storage. If the data are maintained only once in an organisation, storage is reduced. Furthermore, a variety of DSS can use the same databases in different ways. The data are linked together so that information from different physical locations on the storage medium can be joined together for transmission to the users screens with a minimum of trouble. As the application needs change, the addition or removal of a field can be performed efficiently. Furthermore, decisions can be coordinated more easily because everyone is using the same updated version of the data (McLeod, 1995).

Since the storage can be adapted to a particular application, it can be stored efficiently for that application, thereby making the processing easier, cheaper and faster. All these benefits sound good until the application is changed and the needs change. Then users must start all over again and rebuild the databases at great expense and effort. These costs, coupled with the ease of merging data, the increased number of fields available, the longer time horizon that is generally available, and the reduced cost of maintenance, helps to sway the preference towards database technology.

Although the database provides the foundation of a DSS, providing data about a vast array of issues which then serve as the foundation of models, these data are not sufficient to support most decision making. Data are available from a variety of sources (Adriaanse *et al.*, 1996).

4.11.4 Database management systems

The primary advantage that the database management system provides is an independence between the actual arrangement of data (as they are physically represented) and the apparent arrangement of data thereby providing the translation to the application. Users can have access to the same data, displayed on the same type of screen and manipulated in the same fashion, as they had in the file-processing application. As applications improved or new applications are added, they simply need to be hooked to the database management system, saving considerable time in development. Even the process of adding new fields to the database is considerably easier than adding them to traditional files. Hence, since more applications provide greater access to more data and do more with the data than before, organisations were willing to support the concept (Dhar and Stein, 1997).

The database approach is particularly important when data access across functional and organisational boundaries are desirable, and when future needs are uncertain with regard to the type of data that are important and/or associations between data fields. In addition, database technology is important when users frequently need rapid access to data to answer ad hoc questions. All these reasons imply that the database technology is crucial to providing the kind of flexibility necessary to maintain DSS (Sauter, 1997).

When considering database technology from the perspective of DSS, it is important to note that not all database structures are equal with regard to flexibility and/or usability. There are three fundamental database structures; hierarchical structure, network structure and relational structure, each of which have advantages and disadvantages. In light of these advantages and disadvantages, the relational structure is the most promising from the perspective of DSS.

Clearly the dictate that most data would be held centrally would not cause departments to abandon the traditional file-processing philosophy. The impetus arose as a result of the introduction of database management systems to facilitate the use of databases. The database management system serves as a buffer between the needs of the applications and physical storage of the data. It captures and extracts data from appropriate physical location and feeds it to the application's program in the manner requested. Maintenance is a problem. It is easy to create loops as users attempt to form new structures. Similarly, every time new information is added to the database, the pointer system needs to be updated, which does not facilitate flexibility (Dhar and Stein, 1997).

4.11.5 The data warehouse component

The alternative to an operational database is to create a data warehouse to support the DSSs needs. A data warehouse is a database management system that exists separately from the operations system. It is subject and time variant and integrated, as are the operational data (Kelly, 1995). However, data warehouses are nonvolatile and hence capable of supporting a variety of analyses consistently. Generally, these databases are archives for operational data that have been chosen to support decision making and optimised to interact with the DSS of an organisation (Singh, 1998). Frequently, they are relational databases that can support a wide variety of queries in a wide variety of formats and may be composed of hundreds of tables optimised for typical queries.

The development of a data warehouse is a difficult and time-consuming process with considerable costs (Anahory and Murray, 1997). While the process of moving and optimising data are not difficult, the process of identifying relevant data, blending them and ensuring that they are scrubbed appropriately are difficult. In addition, in order for the warehouse to be most effective, designers must identify key fields on which to index the data and a format for indexing that makes data use most efficient. Once the data warehouses have been created and optimised, it is a straightforward process to load them efficiently, loading new data when decision support activities are not being performed. However, as data are multiplied over time, new syntax and query formats that are faster and easier need to be defined, as well as new approaches for joining relational tables and for mining these very large databases using 'intelligent agents'.

Although data warehouses provide access to information that will help decision makers understand their operations and environments better, users can become lost in the enormous possibilities for analysis (Gray and Watson, 1998). A less experienced user might need tools to help 'mine' the value of the information available in these warehouses. Such a tool could assist users to find the kinds of data that differentiate, among the best alternatives, identify cases that meet some criterion and then summarise the result or find patterns in the data to highlight important trends or actionable situations.

4.11.6 The model component

Modelling is defined as the simplification of some phenomenon for the purpose of understanding its behaviour. Environmental models fulfill the same objectives. Within the environment, the purpose of a model is to simplify the choice context so that decision makers can clearly understand options and potential ramifications. Models represent an important part of decision support systems. Most environmental decisions have a large number of influential factors. Hence, most decision makers need to filter the essential components of the situation from the irrelevant ones. While it seems obvious that models fulfill this need, not everyone feels comfortable with models. Often it is not clear what model is most appropriate. Other times, it is clear what kind of model is needed, but the data are not there to support it. Finally, sometimes it is not the result of the model that is so important, but rather the model's sensitivity to particular conditions (Sauter, 1997).

Although models can be applied without DSS, their power is magnified with DSS because of the inherent flexibility, friendly interfaces and query capabilities of DSS (Fisher, 1999). Historically, decision makers needed to rely on others to develop and interpret models for them because of the difficulty of running the computer programs associated with models. With DSS, decision makers are given personal access to appropriate models and appropriate data, and immediate access to results (Sauter, 1997).

It is this easy, friendly access that makes DSS-based models so attractive. Decision makers can understand the implications of their judgement and modify those judgements when they appear to be inconsistent with what is known (Davis, 1989). In addition, because of the speed and efficiency of analysis, decision makers can examine more alternatives in order to find a good strategy. Furthermore, the model encourages decision makers to investigate the variables that are most sensitive to assumptions. Improvement in these aspects of problem analysis, in turn, aids decision makers in advocacy and implementation of the chosen solution because they better understand more facets of the problem.

DSS can include several types of models. The characteristics of models differ substantially, as do their uses; each represents simplification of a decision phenomenon that is useful for understanding some component of behaviour. The skills needed to build and use these models and the kind of support needed to help a less skilful user utilise the models effectively, also differ considerably. Part of the challenge to creating a DSS is knowing what models need to be included and how they can be supplemented to make them meaningful and useful for the decision maker (Cole and King, 1968).

Three different dimensions used to describe models include: the representation dimension, the time dimension and the process dimension as illustrated in Figure 4.2 (Chorley and Haggett, 1967; Cole and King, 1968; and Chorley and Haggett, 1969).

The task of the model-based management system is to help the decision maker understand the implications of using a model. This is not always easy as the decision makers may not be inclined to ask questions, particularly if they do not know what questions need to be asked. It is important therefore to provide enough of the appropriate information for the decision maker to understand the phenomenon of interest.

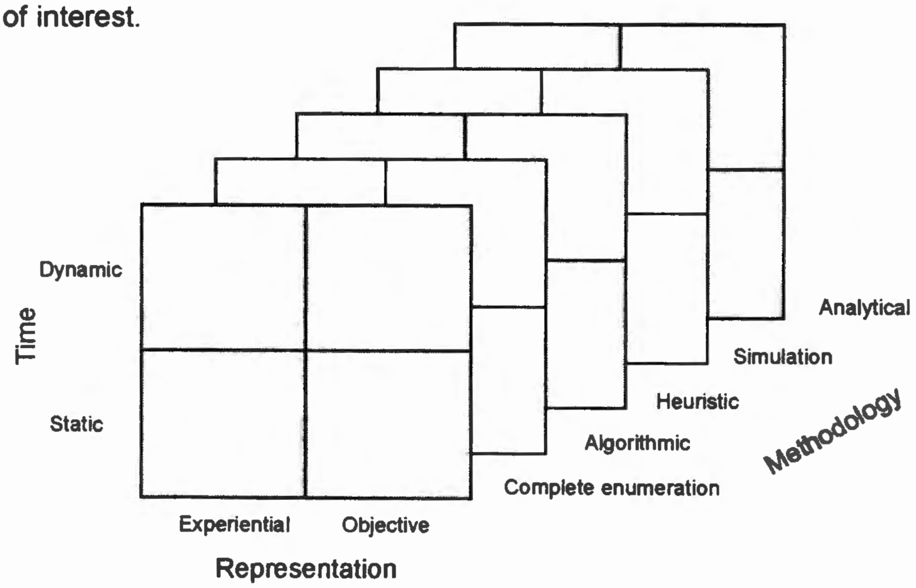

Figure 4.2: The representation, time and the process dimension of model descriptions (modified after Chorley and Haggett, 1966; Cole and King, 1968; and Chorley and Haggett, 1969)

The 'Help' button provides information about the kinds of analyses that might be accomplished to further investigate the topic. Thus, allowing the decision maker to explore the relationships through whatever analysis is deemed appropriate. Such an option can allow an unknowledgeable decision maker to learn more about the decision environment. It can also allow the knowledgeable decision maker to pursue some subtle clue that is suggested by some earlier result. Although appropriate in some cases, a general rule for selecting between these options is the higher in management or the less statistically trained the person, the fewer non-significant analytical results the DSS should show.

4.11.7 The GIS component

The history of using digital computers to handle and analyse mapped data incorporate the origins of GIS. Geographical information is information about geography bound to some specific set of locations on the earth's surface (Johnson, 1999). The term GIS is fundamentally about the use of digital data to represent space and time (Couclelis, 1999). The foundations of GIS arise from distinct origins namely:

- ❑ the need for computers to perform certain simple but enormously labour-intensive tasks - if a map could be represented in digital form, then it would be easy to make measurements of its basic elements and specify areas assigned to various classes (Coppock, 1962).
- ❑ the benefits of automating the map production process - once information of any kind is in digital form, it is much easier to manipulate, copy, edit and transmit (Rhind, 1988).
- ❑ landscape architecture and environmentally sensitive planning - in which a view of planning emerged, that saw the world as composed of a set of largely independent layers, each representing some component of the environment, and thus some set of environmental concerns (McHarg 1969).
- ❑ urban and demographic efforts to automate national population census requiring the tabulation and publication of statistics for a range of geographical units, with complex hierarchical relationships in space.
- ❑ development of remote sensing as a potentially cheap and ubiquitous source of Earth observations (Star *et al.*, 1997).

In 1980, the GIS collective was dominated by the disciplines of landscape architecture, urban and regional planning, geography, cartography and remote sensing. The rapid growth of GIS has resulted in new alliances with computer science, computer graphics, computational geometry and database theory and increasingly being seen as a specialised sub-field of information technology and information science (Longley *et al.*, 1999).

The initial perception of GIS was of large-scale software integration around a common data model. Since GIS made it possible to store many coverages, software development was seen as providing a large number of functions to operate on those layers, as well as basic housekeeping functions for input, storage and output (Weibel and Dutton, 1999). The view began to crumble in the early 1990's as the distinction between geographical and other types of data became less evident. Expensive packages which optimised the use of available computer power did not necessarily mean that individual GIS operations were performed in the most efficient manner. There was a growing resistance to solutions that required customers to acquire all functions, regardless of need. Customers thus became frustrated with the direct and indirect costs of the large scale software solutions (Longley *et al.*, 1999).

On the basis of these problems, GIS has been reinvented to incorporate the vision of a collection of interpolated modules, under common standards. The growth of electronic communications networks and associated applications means that it is no longer necessary for the data, the software and the user to be in the same place at the same time. The advent of powerful personal computers (PC's) has provided substantial GIS functionality (Longley *et al.*, 1999), dispensing concise, relatively stable and easy to use desktop packages to use on the individual desktop.

Over the years the vision of GIS has shifted significantly, but has always included the concept of processing geographical information within an integrated environment. Today, the term GIS tends to be applied whenever geographical information in digital form is manipulated, whatever the purpose of that manipulation (Peuquet, 1999). Because GIS implies a generalised software environment that is exclusive to geographical information there is a tendency for it to be most strongly associated with multi-disciplinary, integrative work and applications, in more narrowly defined environments less general solutions may be adequate (Kraak, 1999). The continued existence of GIS relies on the belief that there is some value in dealing with geographical information.

GIS is a young area of technology innovation and application as well as a rapidly changing one. Developments in computer technology have contributed significantly to the technology advances of GIS. The most significant technological advancement that has impacted on GIS is the improvement of computer hardware (Anselin, 1999). As a result of these developments, hardware systems have become faster and cheaper and their physical size has decreased. The full implications of improvements in computer processor speed have still to be fully recognised in GIS applications. Some of the hardware performance increases have been seen by the development of ever more sophisticated graphical user interfaces (GUI's), while the emphasis in spatial analysis has been used to enhance hardware performance to support visualisation and data exploration rather than data modelling as more traditionally conceived (Longley *et al.*, 1999).

Only a few years ago, the engineering workstation with its UNIX operating system was the dominant platform for delivering GIS. Since then, there has been the shift towards the personal computer, the innovation of desktop computing and the gradual domination of Microsoft and Intel's microprocessors. By 1997 the Intel combination had become the system of choice for GIS applications on the desktop. For server machines and specialist applications, UNIX remains a credible and important alternative. But Windows has become so widely adopted in GIS applications because of its widespread use in general applications, its comparative ease of use, its ability to run both GIS and non-GIS applications and its low cost. As a consequence, the major GIS software systems have a remarkably similar 'look and feel'.

One of the fundamental characteristics of GIS application has been their use of large quantities of multi-dimensional data and the need for multi-user access to spatially continuous databases (Worboys, 1999). The early GIS software systems used binary flat files to store data and specialist data management routines for data organisation and access. Fairly quickly, with the rapid growth of relational database management system technology, many software developers began to manage non-geometric data using relational database management system (Worboys, 1999). Today, the issues of performance, multi-user access and data compression have largely been resolved and it is the norm for GIS software systems to store both geometric and non-geometric data in a relational database management system . With the development of object-relational database management systems and their capabilities of extension to manage complex data types, these are expected quickly to become the standard (Maguire, 1999).

A typical GIS consists of a data input system which collects and processes spatial data; a data storage and retrieval system; a data manipulation and analysis system which transforms the data into a common form allowing for spatial analysis; and a data reporting system which displays the data in graphs or maps (Adriaanse and Linggaard-Jørgensen, 1997).

Most early GIS's were individual isolated islands of technology (Longley *et al.*, 1999). Since then, the rise in importance of network technology has had a profound impact on GIS. In the late 1980's there was a move to connect machines together using local area network (LAN) technology. More recently, wide area network (WAN) technology has been of interest to users. None of these can really compare, however, to the growth in interest and rapid uptake of the Internet as a network-based technology.

The Internet is the world's largest public network. It is a multi-faceted mosaic of computer servers supplying information upon request to multiple clients. The Internet is unified by common use of the Internet Protocol (IP). This communication standard allows heterogeneous hardware to communicate in a simple, but effective, fashion (Longley *et al.*, 1999). The World Wide Web (www) is a popular application which operates over the Internet. The www is a distributed collection of sites (servers) composed of multimedia documents. These are linked together using the hypertext transmission protocol (http) and are spatially references using a uniform resource locator (URL). The use of the www has increased at a truly incredible rate in recent years, establishing new standards for many types of GIS application. Those focussing on data publishing, simple display and query have been most successfully implemented.

Allied with the development of the Internet, open object standards and object brokers have been used to support distributing computing. The Java language has provided a means for sending program modules over the Internet as well as data, allowing one system to send a process for another system to execute. Each of these developments is contributing to a new Internet-based computing environment in which it is as common to distribute the ability to process as it is to distribute data for processing (Longley *et al.*, 1999). The combined effect of the application of these technologies is that GIS software is breaking up into reusable 'plug-and-play' modules, which can be assembled and used through the Internet. Each of these advantages in technology has, of course, been designed to improve the ability to store, manage, manipulate, display and query geographical data (Egenhofer and Kuhn, 1999). Together they have also profoundly changed the way that computing is carried out, as the practice of a user interacting with a file server becomes supplemented by 'peer-to-peer' computing in which every user is potentially both a client and a server - both a source and a destination for computation (Maguire, 1999).

4.11.8 User interface components

To the decision maker, the user interface is the DSS. The user interface includes all the mechanisms by which commands, requests and data are entered into the DSS, as well as all the methods by which results and information are output by the system. It does not matter how well the system performs. If the decision maker cannot access models and data and peruse results easily, the system cannot provide decision support. In fact, if the interface does not meet their needs and expectations, decision makers will often abandon use of the system entirely regardless of its modelling power or data availability (Davis, 1989).

The key to good user interface design is to present information in such a way that users can avail themselves to the full potential of the system. Today, this is more an art than a science. With experience designers become more attuned to what the users want and need and can better provide it through good colour combinations, appropriate placement of input and output windows and generally good composition of the work environment. Aspects of the user-interface component include: the action language, the display of presentation language, the knowledge base and the modes of communication.

4.11.9 The mail component

Historically, the mail system, even the electronic mail system, was seen as an auxiliary function of DSSs (Chittenden, 1995). Thus, although decision makers would have access to email delivery systems, they would not be used as part of the DSS. To use email, decision makers would first need to stop processing the DSS. Even with the advancement of 'windowing' technology, the two were still independent applications.

Today's electronic environment allows for the integration of DSSs with an email system as a productive enhancement tool. As an interface, the email system allows the decision maker greater access to discussion groups, Internet databases and other electronic data and tools for decision making. These resources can extend the range of available information and can, in some cases, provide access to more timely data. Further, the use of email can help decision makers to communicate with colleagues to clarify information and analyses as well as to establish a shared perspective of solutions, all of which are important steps in the decision making process.

An adequate email system is one that has features that make it useful for decision making. Such systems should have available the conventional email features as well as the ability to log the messages, delete the messages, forward the messages to other interested individuals and reply to

the messages. In addition, they should have an easy and automatically accessible notebook of individuals and the email addresses (Sauter, 1997).

4.12 Decision Support System misconceptions

The use of a DSSs does not involve computer programming and data entry. Thus, decision makers do not write computer code to analyse data when using the DSS. Rather, DSSs present a framework through which decision makers can obtain necessary assistance for decision making through easy-to-use menus or command systems. Such a system, generally provides help in formulating alternatives, accessing data, developing models and interpreting the results, selecting options or analysing the impacts of a selection. In a similar fashion, decision makers do not generally enter data when they use a DSS. Instead, databases already available are used which can be substantiated by further research if necessary. Another DSS misconception is the misunderstanding that DSSs simply involve the use of spreadsheets and modelling packages. Spreadsheets and modelling packages, therefore, simply provide the tool to do analysis and do not provide a mechanism for accessing data. Furthermore, these tools do not provide assistance in the wide range of decision support generally associated with a DSS (Sauter, 1997).

4.13 Chapter summary

The development and design of DSSs as a tool to facilitate in the decision making process with respects to environmental management was appraised in Chapter Four. EDSSs are a new approach in the environmental field within South Africa. However, a review of the development of DSS and knowledge obtained from past experiences contributed positively as a basis for the development of a new EDSS. Origins of the first DSS were founded in the business sector as a result of the increasingly practical nature and rapid changes in computer technology in the 1960's. Access to information has the effect of empowering the decision makers to analyse information in a manner that is helpful to a particular decision as well as providing interactive support. In this way, the opportunity to improve data collection and analysis processes associated with decision making is improved. DSSs cover a wide scope of environs ranging from strategic planning to operations management. On this basis, it is often difficult to determine when the use of a DSS is beneficial. As a rule, DSSs are most useful when it is not obvious how the choice should be made.

With respect to EDSS, four components and tools are available, namely; the database management system, the model base management system, the user interface and the mail management system. Together these components comprise an EDSS. Although these components are complex and the concept of EDSS technologically advanced, the strategy and approach to attaining solutions in a complex, integrated environment becomes possible. Over time and through experience such systems will become more common place and user friendly thereby bridging the gap between the developer and the end user or stakeholder. EDSSs, therefore, present a framework through which decision makers can obtain the necessary assistance for confident decision making with regards environmental management.

CHAPTER FIVE

5 THE MOOI RIVER CATCHMENT: A CASE STUDY FOR ENVIRONMENTAL DECISION SUPPORT SYSTEMS

5.1 Introduction

The Mooi River Catchment, located on the Far West Rand, has traditionally been an area of extreme economic value to South Africa as a result of the extensive gold mining industry established in the region (See http://www.ccwr.ac.za for site map). Gold was first discovered in the area in 1886 by Australian prospector, George Harrison, on the farm 'Langlaagte' located on the western outskirts of present day Johannesburg. The full extent of these reefs was only later revealed to extend over an arcuate area of approximately 500 km, extending from Virginia in the Free State Province, through Klerksdorp and Stilfontein in the North West Province; Carletonville, Westonaria, Krugersdorp, and Johannesburg in the Gauteng Province through to Kinross in the Mpumalanga Province. These deposits constitute the largest known deposits of gold in the world and still contribute more than half of the annual world production of newly mined gold. As Johannesburg and the surrounding towns developed, so to did the need of a water supply and agriculture to sustain the growing population. Pumping and dewatering of the unique dolomitic compartments located in the western area by the gold mines was a later issue.

The complexities of the Mooi River Catchment make it an ideal catchment for the introduction of an EDSS. The shortcomings of past studies in the region, of which there are numerous, arise out of the inability for information to be shared in a time-series and spatially interlinking perspective. However, the environmental problems of the catchment go beyond the studies and lack of sharing information. The main concerns in the Mooi River Catchment arise from past discrepancies and lack of trust between the stakeholders of the catchment.

The aim of the case study is to develop an interactive, real time EDSS for the Mooi River Catchment that can facilitate environmental 'best practice' management for broad spectrum applications. The development of an EDSS for environmental management, needs to focus on supplying information to Catchment Management Agency's (CMA's), stakeholders, researchers and resource managers to support in the decision making process. The EDSS should be able to identify and meet these information needs as far as possible. It is only by understanding the functioning of environments and the response to change that the development and application of EDSS can contribute meaningfully towards sound environmental management. In February 1998, a project was proposed by the North West Province Department of Tourism, Environment and Conservation to develop an EDSS for the Mooi River Catchment. The aims of which are to structure an EDSS that improves communications between managers, researchers and stakeholders as well as to provide information regarding management of the natural environment. The Mooi River Catchment was selected on the basis that it is an environmentally complex catchment. If the EDSS developed could withstand the rigours and complexities presented by the Mooi River Catchment, then the system could handle other catchments within the region.

Cross referencing to the foregoing theoretical framework chapters will be given in brackets and the applicable section denoted by the symbol §.

5.1.1 The decision support approach

An EDSS (§ 4.11) for the Mooi River Catchment will provide a framework (§ 4.8) for CMA's, stakeholders, researchers and resource managers to identify where their expertise and information (§ 4.11.2) are complementary to the project goals, and how they might contribute to the achievement of future project goals (§ 3.3). The structure and form of an EDSS are shaped by the management objectives of the users (§ 3.2). In this case, the broad objective is the sound management of the environment of the Mooi River Catchment. Hence, it is worthwhile to examine more specific purposes and objectives of a DSS for the Mooi River Catchment, since this will guide us towards the development of a preliminary framework for the DSS.

5.1.2 Aims of the DSS approach for the Mooi River Catchment case study

The effects of water pollution may extend well beyond the normal catchment limits. Many water users, including formal and informal agriculture, industry and people requiring domestic water supply, can lay valid claims to water from these rivers. As development and population numbers increase, competition for the water resource becomes more intense. Determination of environmental or water requirements invariably involves consultation with experts in the different fields of environmental science. Therefore, the DSS should facilitate communication between managers, researchers and stakeholders. This will allow managers to improve the quality of their decisions by having access to information. The knowledge base behind the DSS should include the best available information on the natural environment of the Mooi River Catchment. In addition, the DSS should also contain the expert judgement of scientists and the experience of managers. The DSS should be able to be used by system managers to make decisions regarding short and long term management in general. At times, decisions will have to be taken on the basis of the best available data of knowledge (§ 4.9), and the DSS will have to be flexible enough to allow this.

Stakeholders often place emotional, aesthetic or moral value on the natural environment. These values must be recognised and taken into account in setting and implementing policies for river and environmental management. The DSS needs to provide protocols for communication between managers, stakeholders and specialists to allow everyone to participate in the setting of long term conservation and/or management goals for rivers, in local, regional and national contexts (§ 3.7).

It has been implied that one of the goals of the Mooi River Catchment project is to promote the flow of high-quality information among decision makers, system managers, stakeholders and researchers. If the DSS is correctly designed (§4.5), information can be identified well in advance of the decision making process. Adequate time and resources can then be allocated to the collection and processing of the necessary information. The DSS should allow the identification and prioritisation of research activities which will meet information requirements either in advance of or during decision making. In this way research funds can be allocated and used most cost-effectively without reinventing the wheel.

5.1.3 Ideals of an environmental decision support system for the Mooi River Catchment

The DSS should accept input from various sources (§ 4.1 and § 4.9). Correct identification of organisations and people who need to interact with the DSS is important (§ 4.9 and § 4.11.8), as is the manner and form in which information is communicated to and from these people. Inputs to the DSS from decision makers and managers take one of two formats:

- ❑ researchers act and managers react (researchers undertake investigation, managers then use the information to plan and define future development potential in a catchment)
- ❑ managers act and researchers react (managers have a planned or prepared scenario, researchers are then asked to predict and evaluate consequences of such scenarios, and compare different scenarios in term of acceptability)

Often managers do not state explicitly their information requirements or the relationship of these requirements to their management responsibilities and capabilities (§ 4.11.2). This is partly because managers do not have a detailed understanding of environment functioning and responses to management actions (§ 3.2). However, another reason is the practical day-to-day environmental management can seldom be carried out at fine scales (§ 3.2). Very often, all that can be managed with any confidence is at fairly coarse scales which approximates to kilometres.

Research information and scientific expertise should be inputs into the EDSS. The data complexity and coverage needed would be determined by the information requirements of the managers. It is here that there must be close links with the information management programme (§ 4.11.4). The EDSS should be used to inform researchers of specific research information requirements, and should provide agreed protocols for acceptance and incorporation of research information into the decision making process. An objective of the EDSS must be to formulate protocols for the translation of reasonably broad management information requirements into a detailed statement of the issues in question. These would be, in effect, detailed terms of reference for those activities which must be carried out to provide the necessary information (§ 4.5).

The EDSS should facilitate interaction between managers at different levels and in different areas of authority and responsibility, as well as between researchers from various disciplines and at different levels. More importantly, the EDSS should promote interaction between managers and researchers (§ 3.2).

There should also be protocols for appropriate feedback and interaction between managers, researchers and stakeholders at various stages of the decision making process. From the inception of the decision making process to the point where the decision is taken, the EDSS should be used to define clearly: the tasks required of managers and researchers; the scope, complexity and sequence of all tasks; the identification of the necessary expertise required to carry out the tasks; and the protocols for implementation, monitoring and feedback after the decision has been made. There should be a defined product or outcome at each step of the process, with provision for evaluation of the products in terms of satisfactory levels of confidence (§ 4.2 and § 4.4).

A clear definition of the problem or information requirements of managers, translated into terms which can direct researchers is required. If the scenarios proposed by management are judged to be unsuitable, alternative scenarios or modifications should be put forward as documented output. Acceptance or rejection of recommendations and/or modified scenarios proposed by researchers may have consequences for long-term sustainability or environmental management (§ 3.2 and § 3.6). The consequences need to be documented and communicated to managers. Once researchers have provided a response to managers' information requirements, they should also provide documentation on how that response should be incorporated into the decision making process; implementation of any proposal; monitoring and evaluation of any further consequences of implementation; and possible modifications. All output from the EDSS, whether it is in the form of quantitative or qualitative statements, should be accompanied by a statement of the confidence of researchers in their predictions of ecological response to scenarios; the cost implications in terms of additional research, time and resources needed to improve the confidence level; and a statement of the acceptability to ecologists and stakeholders of the predicted change if any.

In order to populate the EDSS, an extensive bibliographical research project was undertaken. These data were used to help populate the data management files and is explained in greater detail in Section 5.4.3.

5.2 Environmental setting

Previous studies undertaken in the Mooi River Catchment are numerous. Initially due to the need for water supply to the developing city of Johannesburg, and later as a result of the extensive gold mining and dewatering of the dolomitic compartments. Recent studies have been concerned with and concentrated on the environmental impacts of the gold mines and their effects on the surrounding environments, namely surface and ground water resources, the effects of tailings dam and rock dumps and to a lesser degree, pollution associated with river and dam sediment. On this basis, the environmental setting for the region is well substantiated. Documentation and previous studies pertaining to the environmental setting of the Mooi River Catchment are documented below in Table 5.1 and can be reviewed in Appendix A. Selected studies were used to populate the WDM.

Table 5.1: Environmental setting documentation for the Mooi River Catchment

Topic	References
Geology	du Toit (1921); du Toit (1939); de Kock (1964); Burger and Coertze (1973); Burger and Walraven (1975); Coertze *et al.* (1978); Tankard *et al.* (1982); DMEA (1989); Envirolink (1995a); SRK (1996a); SRK (1996b); SRK (1996c)
Topography	1: 50 000 map series Surveyor General
Drainage	DWAF (1998)
Land types	1: 250 000 map series; King (1953); Hammond (1964); Kruger (1973); Verster (1973); MacVicar *et al.* (1977); Land Type Survey Staff (1984); Bezuidenhout (1993)
Soils	Land Type Survey Staff (1984); Bezuidenhout (1993); Koenig (1998a); Koenig (1998b)
Land use	1: 50 000 map series Surveyor General
Climate	Potchefstroom Weather Station 1961 to 1990; Carletonville Weather Station 1961 to 1990; Krugersdorp Weather Station 1961 to 1990

Surface water	Irving (1958); Henzen and Murray (1967); Stoch (1968); CSIR (1969); DWAF (1969); Die komitee oor gehalte van water aan die verre Wesrand (1971); Sviridov and Oliver (1988); SRK (1989); Pohlandt-Watson and Jones (1990); CSIR (1991); Pulles (1992); Coetzee and Szczesnaik (1993); Pulles (1993); Council for Nuclear Safety (1994a); Council for Nuclear Safety (1994b); AEC (1995); McPhail (1995); Schoonbee *et al.* (1995); AEC (1996); Coetzee (1996); Envirolink (1995b); BKS, Stewart Scott and Ninham Shand (1997); Wipplinger and Coetzee (1997); Chevrel *et al.* (1998); Opperman (1998); DWAF (1998); Mooi River Standards Committee (1999)
Ground water	Kriel (1953); Geological Survey (1954); DWAF (1958); Kent (1958) Kriel (1958); Jordaan *et al.* (1960); Interdepartmental Committee (1960); Brink and Partridge (1965); Jennings (1965); Keersmaekers (1966); Enslin and Kriel (1967); Geological Survey (1967); Weavind (1968); Keersmaekers and Aldridge (1967); van Woerkom (1968); Department van Landbou-tegniese dienste (1969); Fölscher and Barnard (1969); van Woerkom (1969a); van Woerkom (1969b); Venter (1969); Kleywegt and Enslin (1973); Fleischer (1977); Fleischer (1978); Temperley (1978); Fleischer (1979a); Fleischer (1979b); Fleischer (1979c); Fleischer (1981a); Fleischer (1981b); Vegter (1983); Morgan and Brink (1984); Vegter (1985); SRK (1986); Basson (1988); Connelly (1988); Vegter and Foster (1989a); Vegter and Foster (1989b); Bredenkamp *et al.* (1991a); Bredenkamp *et al.* (1991b); Simonic (1993) Van Wyk and Louw (1993a); Van Wyk and Louw (1993b); Walton and Levin (1993); Issar (1994); Bredenkamp (1995); van Rensburg (1995); Simonic (1997); Erasmus (1998)
Natural vegetation	Acocks (1975); Land Type Survey Staff (1984); Acocks (1988); Bezuidenhout (1988); Bredenkamp *et al.* (1989); Bezuidenhout and Bredenkamp (1990); Bezuidenhout and Bredenkamp (1991a); Bezuidenhout and Bredenkamp (1991b); Bezuidenhout and Bredenkamp (1991c); Bezuidenhout and Bredenkamp (1991d); Bezuidenhout (1993); Bezuidenhout *et al.* (1993a); Bezuidenhout *et al.* (1993b); Bezuidenhout *et al.* (1993c); Bezuidenhout *et al.* (1993d); Bredenkamp *et al.* (1993); Bezuidenhout *et al.* (1994) Rutherford and Westfall (1994); Bredenkamp and van Rooyen (1996)
Socio-economic structure	Stats SA

5.3 Environmental problems associated with the Mooi River Catchment

The majority of the environmental problems within the Mooi River Catchment over the past century have arisen from problems associated with the extensive gold mining in the region. Population growth and increased water utilisation are symbiotic. As the population increases over time, so too does the requirement, demand and dependence on the water resource. Additional pressure is exerted on the available water resource by settlements as they move away from the more established centre areas. In such instances, the available water resources need to be distributed over a wider area, thereby placing additional stresses on the system. The expansion of Johannesburg due to the discovery of gold is such an example. Water commissions have been in operation in the greater Johannesburg region since 1894 (Ramsden, 1985) as a means to supply potable water. Thus, since 1894, water management in the Mooi River Catchment has been an area of concern to supply potable water to the surrounding settlements.

In a similar vein, as population increase so too must the development increase to supply the growing population with its needs. Development expansions can take the form of industrial, mining, agricultural or recreational needs - each of which requires a share of the available water resource. During such processes, the volume of water may be reduced and the quality of water may deteriorate. It is, therefore, fundamental to manage water resources in such a way as to sustain the human development, for the benefit of all communities, the ecological environment and to satisfy basic human needs (DWAF, 1998). The development expansions mentioned above have the potential to establish environmental problems that may affect the Mooi River Catchment. Generic factors affecting the water resource are highlighted and discussed in greater detail in § 2.4.

However, the role of gold mining in the catchment and its effect and impact on the surrounding environment within the Mooi River Catchment deserves more attention. The abundance of operational gold mines in the area, many of which have been in operation for over 50 years, result in a distinct set of environmental problems endemic to the area. Surface water systems are thus characterised by aspects such as (Pulles *et al.*, 1996):

- strong point source effluent discharging saline and acidic effluent in to the surface water environment;
- old, non-operational slimes dams (often poorly- or un-rehabilitated) in or close to natural water courses, resulting in substantially high saline and acidic diffuse pollution sources;
- extensive old surface infrastructure (including various defunct shafts) which can not be properly maintained due to lack of staff and funds - typically associated with declining ore grades; and
- ongoing reclamation of surface sand and rock dumps.

5.4 Methodology

The complexities of and the environmental problems in the Mooi River Catchment lend themselves to the advent of an environmental computer-based EDSS (§ 4.11). The development of an EDSS was a logical and systematic step considering the various studies and research that had previously been undertaken in the catchment. These studies, from 1894 (Ramsden, 1985) culminate with the situational analysis of the Mooi River Catchment undertaken by the DWAF in 1998, eventuating in an enormous amount of data and information pertaining to the Mooi River Catchment. Major research has been conducted to determine the identification and extent of environmental impacts, the factors causing the impacts and the proposals for alleviating the impacts. What is missing, is the provision for decision makers across the spectrum of the public and private sectors including authoritative bodies, developers and IAP's with a DSS based on environmental considerations in order to facilitate holistic and environmentally sound decision making (Van Riet *et al.*, 1994). Some form of EDSS is, therefore, needed to manage all the data from the previous studies. However, the EDSS should also fulfill other roles including being able to be used extensively by stakeholders and the CMA of the Mooi River Catchment to identify possible gaps in the existing knowledge. Additional attributes such as the ability to identify pollution sources and mitigate measures to combat pollution problems need to be included.

5.4.1 Software selection

The need for an EDSS has been identified based on the enormity of the environmental problems within the Mooi River Catchment. However, this is only the first step in the process. The requirements of the EDSS are paramount. Such a system should exhibit the key characteristics of compatibility, inter-operability, inclusivity, functionality and flexibility, affordability and co-ownership (§ 1.1, § 3.3 and § 3.8). A schematic representation of the EDSS is illustrated in Figure 5.1. The design of the EDSS must be sufficiently flexible to allow additional models, for other aspects of the environment such as soils and air to be easily added to the structure, without hindering the compatibility, inter-operability and functionality of the existing system.

On this basis, software that fulfilled the recognised criteria was selected. A large number of software packages are available on the market today, much of which is available to the public at enormous monetary cost. There is, however, public domain software available at an affordable cost that is capable of handling the complexities experienced in the Mooi River Catchment. Such software packages were of interest in the Mooi River Catchment study. By selecting existing, affordable software available in the marketplace, re-invention of the wheel is avoided and time for software development is saved.

The software selected for the Mooi River Catchment to make up an EDSS includes a hydrological model (§ 4.11.6), a data warehouse to store all the available data (§ 4.11.5), external database packages (§ 4.11.3), a GIS package (§ 4.11.7) and a graphic user interface (GUI) (§ 4.11.8). In addition some form of communication component is required such as email (§ 4.11.9). The software selected includes the hydrological model, Hydrological Simulation Program - Fortran (HSPF) and the associated data warehouse, watershed data management (WDM), which is linked to the graphic time

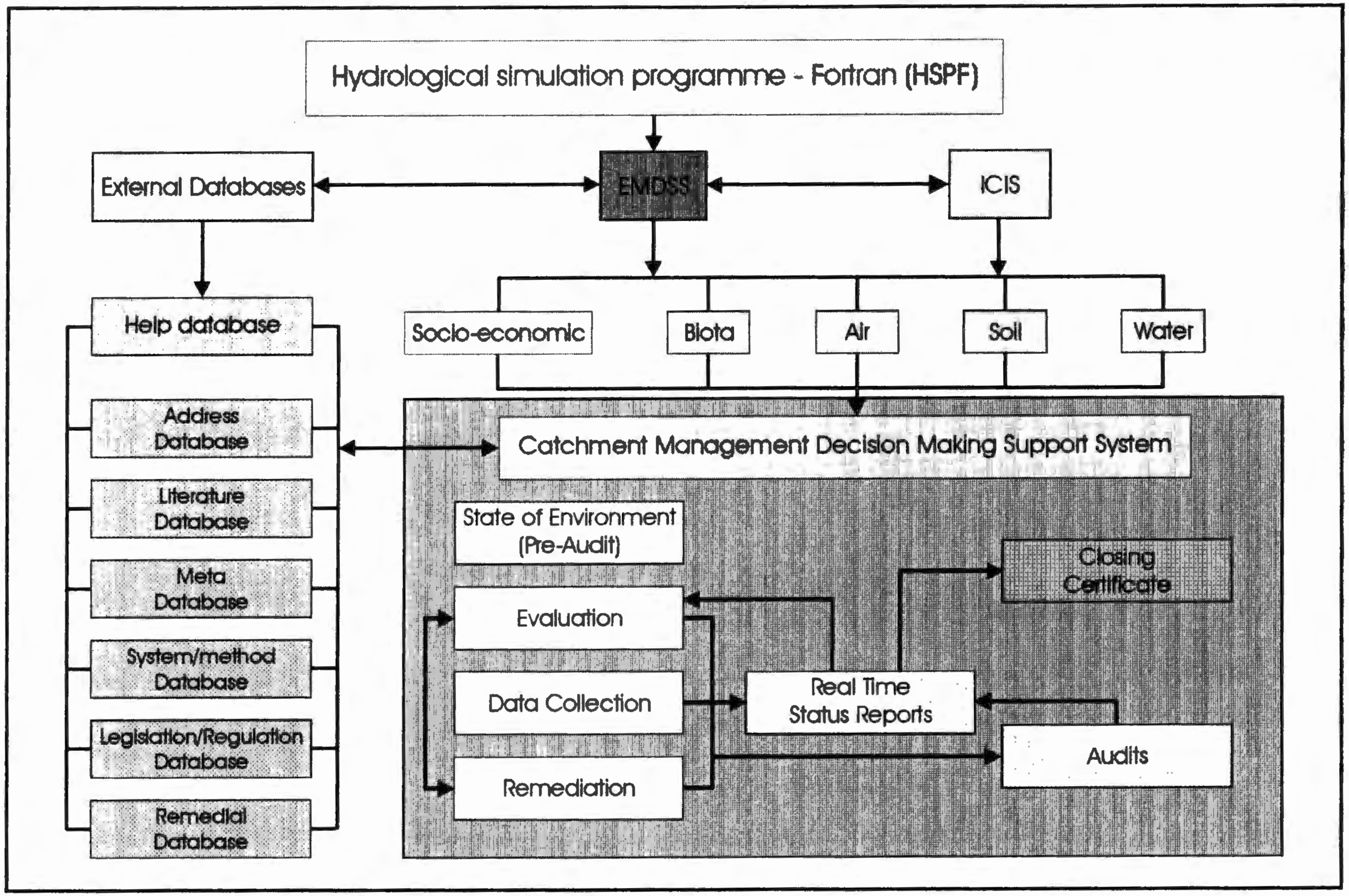

Figure 5.1: A schematic representation of the EDSS for the Mooi River Catchment

series program integrated catchment information system (ICIS) which sits on top of the ArcView package. These software packages are discussed below in greater detail.

5.4.2 HSPF as a tool for decision support

HSPF is a comprehensive, conceptual, continuous watershed simulation model designed to simulate, for extended periods of time (USGS, 2000), all the water quantity and quality processes that occur in a watershed, including sediment transport and movement of contaminants (Hydrocomp, 2000). HSPF simulates interception, soil moisture, surface runoff, interflow, base flow evapotranspiration, groundwater recharge, dissolved oxygen, biochemical oxygen demand (BOD), temperature, pesticides, conservatives, faecal coliforms, sediment detachment and transport, sediment routing by particle size, channel routing, constituent routing, pH, ammonia, nitrate-nitrite, organic nitrogen, orthophosphate, organic phosphorus, phytoplankton and zooplankton (USGS, 2000). Although classified as an accrued model (§ 4.11.6), spatial variability can be reproduced by dividing the catchment into hydrologically homogeneous land segments and simulating runoff from each land segment independently, using different meteorological input data and watershed parameters (Hydrocomp, 2000).

The origins of HSPF are founded in the Stanford Watershed Model (SWM) developed by Crawford and Linsley (1966). Frequently cited in the literature as being one of the first comprehensive watershed models, the SWM has been widely used and has undergone numerous modifications and additions over the years. Crawford and Linsley further developed the original model to create HSP (Hydrocomp Simulation Program), which included sediment transport and water quality simulation components. During the early 1970s, Hydrocomp went on to develop the ARM (Agricultural runoff management model) and the NPS (nonpoint source pollutant loading model) for the US EPA (Environmental Protection Agency). Recognising the limitations of most existing simulation models, in terms of data management and compatibility with other models, the EPA in 1976 commissioned Hydrocomp to develop a system of simulation modules in standard Fortran that was easy to maintain and modify and would essentially handle all the functions performed by HSP, ARM and NPS.

The result was HSPF, which consists of hundreds of process algorithms developed from theory, laboratory experiments and empirical relations from instrumented watersheds (USGS, 2000), set as a series of computer codes that can simulate the hydrological and associated water quality process on pervious and impervious land surfaces and in streams and well-mixed impoundments (Donigan *et al.*, 1984). The model can be applied to most watersheds using existing, continuous meteorological and hydrological data to compute streamflow hydrographs and pollution graphs (USGS, 2000), and includes fitted parameters as well as parameters that can be measured in the watershed. Although data requirements are extensive and learning to use the model correctly requires some time, the model is recommended as the most accurate and appropriate management tool available for the continuous simulation of hydrology and water quality in watersheds by the EPA (Hydrocomp, 2000).

In HSPF, the various hydrological processes are represented mathematically as flows and storages. In general, each flow is an outflow from a storage, usually expressed as a function of the current storage amount and the physical characteristics of the subsystem. Thus, the overall model is physically based, although many of the flows and storages are represented in a simplified or conceptual manner. Although this requires the use of calibrated parameters, it has the advantage of avoiding the need for giving the physical dimensions and characteristics of the flow system. This reduces input requirements and gives the model its generality. For simulation with HSPF, the catchment has to be represented in terms of land segments, reaches and/or well-mixed reservoirs or impoundments. A land segment is a subdivision of the simulated watershed (Hydrocomp, 2000).

The boundaries are established according to the user's needs, but generally, a segment is defined as an area with similar hydrological characteristics. For modelling purposes, water, sediment and water quality constituents leaving the watershed move laterally to a downslope segment or to a reach or reservoir. A segment of land that has the capacity to allow enough infiltration to influence the water budget is considered pervious. Otherwise, it is considered impervious. The two groups of land segments are simulated independently. In pervious land segments, HSPF models the movement of water along three paths: overland flow, interflow and groundwater flow. Each of these three paths experiences differences in time delay and differences in interaction between water and its various dissolved constituents. A variety of storage zones are used to represent the storage processes that occur on the land surface and in the soil horizons. Processes that occur in an impervious land segment are also simulated. The hydrological and water quality processes that occur in the river channel network are simulated by reaches. The outflow from a reach or completely mixed lake may be distributed across several targets to represent normal outflow, diversions and multiple gates on a lake or reservoir. Evaporation, precipitation and other fluxes that take place on the surface are also represented. Routing is accomplished using a modified version of the kinematic wave equation. Frequency-duration analysis can be done for any time series. Any time step from one minute to one day that divides equally into one day can be used. Any period from a few minutes to hundreds of years can be simulated (USGS, 2000).

HSPF is the only available model that can simulate the continuous, dynamic event or the steady-state behaviour of both hydrological or hydraulic and water quality processes in a watershed. The model is unusual in its ability to represent the hydrological regimes of a wide variety of streams and rivers with reasonable accuracy. Thus, the potential applications and uses of the model are comparatively large and include: flood mapping, urban drainage studies, river basin planning, studies of sedimentation and water erosion problems and in-stream water quality planning (Hydrocomp, 2000).

HSPF model was primarily developed as a planning tool to assess changes in water, sediment and constituent movement as a result of land use change (Brun, 1998), reservoir operations, point or non-point source treatment alternatives and flow diversions (Hydrocomp, 2000). In the 1980s, preprocessing and postprocessing software, algorithm enhancements and the use of the USGS WDM system were developed jointly by the USGS and EPA. The WDM system provides a systematic approach to the storage and retrieval of data required to operate models and is discussed in greater detail in § 5.4.3. Programs, such as ANNIE (USGS, 1998a), support data pre-processing and post-processing for statistical and graphical analysis of data saved in the WDM file. The current release of HSPF is Version 11 (Bicknell *et al.*, 1997), an interactive version which was developed by the USGS in the 1990s (Hydrocomp, 2000). An advantage of the HSPF model is that it is continuously being updated and new aspects and features developed.

Meteorological records of precipitation and estimates of potential evapotranspiration are required for watershed simulation. Air temperature, wind, solar radiation, humidity, cloud cover, tillage practices, point sources and/or pesticide applications may be required for water quality simulation. Physical measurements and related parameters are required to describe the land area, channels and reservoirs. Output is either printed tables at a given time step, a flat file or the WDM file. The preprocessing software uses data from the WDM file. Hundreds of computed time series may be selected for the output file (USGS, 2000).

A major disadvantage of HSPF is that it has no graphical user interface (GUI). As a result, a less experienced user can have difficulties in determining model requirements, with setting up the parameters, runs and calibrations of the model. The user must therefore, manually create a user control input file (UCI) which informs HSPF of the watershed and land use delineation, meteorological inputs, modules to be used in the model run, watershed and stream network connectivity and model parameters. Given the complexities of HSPF and the number of tasks it can perform, the manual nature of HSPF can present serious obstacles (Brun, 1998).

To offset some of these difficulties, the USGS developed an expert system for calibrating HSPF known as HSPFEXP (Lumb *et al.*, 1994; USGS, 1994). However, the user must still manually produce the UCI. HSPFEXP then uses the produced UCI to run HSPF. Based on the model output, the HSPFEXP suggests ways to alter model parameters for calibration purposes. However, two major limitations still remain with HSPFEXP namely (Brun, 1998):

- the creation of the UCI is completely manual and can require intensive work depending on the size of the watershed
- there is no visual representation of the watershed which can be a valuable asset to any modelling endeavour

Both HSPF and HSPFEXP are available for DOS and UNIX platforms free of charge from the USGS. The modelling power of HSPF was recently integrated with a geographical information system (GIS) environment with the development of Better Assessment Science Integrating point and non-point sources (BASINS) (Lahlou *et al.*, 1998). Although BASINS was designed as a multipurpose analysis tool to promote the integration of point and non-point sources in watershed and water quality-based applications, it also includes a suite of water quality models (EPA, 1996). One such model is non-point source model (NPSM). NPSM is a planning level watershed model that can be used to assess the impacts of land use change on water quality. NPSM integrates point and non-point sources, simulates non-point source runoff, accounts for point source discharges, and performs flow and water quality routing from land segments to stream reaches and reservoirs. NPSM is essentially a GUI that links HSPF with the GIS environment of BASINS. NPSM obtains information from both the user and from GIS data layers, transforms this information into a UCI, and then calls and runs HSPF. The major advancements made by NPSM are that:

- the UCI is created for the user;
- the UCI can be modified within a GUI to aid in calibration; and
- BASINS provides a visual representation of the watershed

BASINS is built on top of ArcView 3.0a and is only available for Windows platforms. BASINS system files and core datasets examples are available from the EPA. Although these datasets are of no relevance to the South African scenario, they do serve the purpose of acting as a series of tutorials which can be worked through to familiarise oneself working with the BASINS system. More recently, a Windows GUI was created for HSPF called Generation and Analysis of Model Simulation Scenarios (GENSCN). GENSCN allows the user to change the UCI input sequence interactively, run HSPF and analyse the results graphically (http://www.aquaterra.com). GENSCN also provides HSPF users with model parameters for particular applications (Brun, 1998).

5.4.3 Watershed Data Management file system as a tool for decision making

The WDM system provides a systematic approach to the storage and retrieval of data required to operate models (§ 4.11 and § 4.11.5). The WDM system uses a well-defined binary, direct-access file structured accessed through a library of routines to create a file, add data to the file, replace data in the file, get data from the file and delete data from the file. Five categories of data may be stored in the WDM file data sets namely: time series data, table data, text data, vector data and space-time data.

The WDM library of routines enables convenient input, update and output of data. In addition, the WDM files allows (USGS, 1998b):

- ❑ comprehensive specification of data attributes;
- ❑ multiple time steps in single time-series data sets;
- ❑ user-defined formats for data stored as tables;
- ❑ compression of data;
- ❑ improved speed and flexibility of interaction between a model and its database; and
- ❑ automatic file maintenance as the user adds, modifies or deletes data sets.

The WDM file is organised into data sets each of which contains a specific type of data. Each data set contains attributes that describe the data, such as station identification number, latitude and longitude. A WDM file may contain a single data set or as many as 200 000 data sets. Data can be added, deleted and modified, using the input and output for a watershed data management (IOWDM) system (USGS,1998c) which is designed to reformat data to and from the WDM file, without restructuring the data in the file. In addition space from deleted data sets are reused.

The WDM file was initially created for use by the program ANNIE for storage, manipulation, graphical display and statistical analysis of data. With the implementation of other programs capable of accessing data stored in WDM files, the WDM file now serves as a common database from which data are shared among multiple applications and across different computer platforms. Such attributes make the WDM a strong data warehouse tool on which to base the EDSS for the Mooi River Catchment. The WDM file therefore provides users within the Mooi River Catchment with a common database for many applications, thus eliminating the need to reformat data from one application to another.

5.4.4 ArcView GIS as a tool for decision support

The involvement of GIS as a tool for decision support (§ 4.11.7) has come to the fore over recent years due to the significant shift away from the field/object dichotomy and towards the concept of processing geographical data within an integrated environment. It has been argued (Maguire, 1991) that the definition of GIS should include more than the digital environment. In this concept, the people who interact with it are also part of the system. Thus, if defined by its objectives, a GIS is a spatial EDSS (Cowen, 1988).

The ArcView GIS software is a popular desktop GIS analysis tool in South Africa and offers solutions to help create, visualise, analyse and present information better and more effectively. On the basis that most data has a geographical component, ArcView GIS allows for the vision, exploration and analysis of data by location. Thus revealing patterns, relationships and trends that are not always apparent in spreadsheets or statistical packages. In this way, data analysis can make better, more informed decisions.

ArcView GIS is also easy to learn and use. An advantage of the system is that although ArcView GIS is powerful, it still remains flexible. Optional extensions extend the softwares overall functional capabilities as the needs and requirements change. Powerful mapping proficiencies that integrate charts, maps, spreadsheets, tables, graphics and multimedia options such as pictures, video and satellite images all contribute towards the analysis capabilities.

The many applications together with the ability to develop custom applications provide the tools to create specialised solutions for mapping and GIS application. By using Avenue, the software built-in, object-orientated scripting language, application developers and programmers can modify the user interface, create scripts, build custom tools and complete solutions to support specific applications. In this way, ArcView GIS can be customised to meet the needs and requirements of the end users. Other important capabilities include projection utility for shapefile coverage projection and datum transformation, geographic and tabular data editing, comprehensive database access and seamless access to data warehouses. It is the ability for customisation and access to data warehouses that makes this software package so powerful and versatile to the Mooi River Catchment project and forms the basis on which the ICIS software was designed.

5.4.5 ICIS as a tool for decision support

The integrated catchment information system (ICIS) developed by the Computing Center for Water

Research (CCWR) is an endeavour to combine and share as many different types of general and time series data and information between users into one coherent, user friendly system (§ 3.2). With a time series component emphasis, the ICIS software has the advantage of being a process which offers regular, affordable and meaningful communication amongst all stakeholder representatives. In addition, the software provides a process that is flexible, yet will increasingly reveal more information on the system dynamics. In order to achieve such goals, the system needs to be open and transparent with the ability of enabling tacit assumptions and mental models to become discernible. Through such procedures, management can develop the confidence to become more adaptive, generative and forward thinking. To ensure success, the inputs, opinions and requirements of the stakeholder needs to be incorporated in an integrated fashion using simulation modelling that can function in a data poor environment. The endeavours of which should ultimately overcome the barriers of communication between stakeholders which arise from geographic and disciplinary separation (§ 3.2).

One of the most advantageous features of the ICIS includes connectivity of the PC based component of the system to a remote shared computer over the wide area networks (Wan). Each of which is informed and driven by the target market namely resource stakeholders such as a catchment management agency (CMA) which operates within the catchment. Stakeholders will be required to operate within the processes mentioned above, in order to achieve ICM. The development of ICIS follows a hierarchical approach to the presentation of information. For example, the physical component comprises hydrological, geological, geomorphological, landuse and climatological information each of which offers various levels of information. The first level, the overview level, is suitable for the user who would like to gain a brief insight into the catchment. From this level, further detailed analysis, or tools to provide detailed analyses are available for those who would like to obtain more detailed information, continuing up to the level of data required. The same is true for information presented in the ICIS i.e. detailed information for experts in a particular field, less detailed and easier to understand information offering greater perspective for non-experts.

5.5 Data acquisition and input

Data (§ 4.11.1) and information (§ 4.11.2) for all environmental aspects of the Mooi River Catchment were acquired and collected from various sources. The sources include local government departments, national government departments, stakeholders, researchers, academics, farmers and some of the mining houses within the catchment area. The quality and type of data or information differed depending on the source. It was therefore paramount to ensure that the ownership of data was maintained and catalogued in the meta database affiliated to the system.

Available data from previous studies were collected and manually typed initially into spreadsheets using either Corel Quattro Pro or Microsoft Excel. Either format could be used, based on the fact that the ultimate destination for the data was the WDM described above in § 5.4. More importantly, was the format of the data input onto the spreadsheet. As the data had to conform to WDM requirements, the data were input into the spreadsheets in the format:

Name	Latitude	Longitude	Type	Date	Value
25 character description of the sample point	ddmmss degrees, minutes, seconds	ddmmss degrees, minutes, seconds	four alphanumeric character shorthand code to describe the type of data for sampling eg prec (precipitation), disc (discharge)	YYYYMMDDHH year, month, date, hour eg 1999081710	recorded value of the type eg 24.1

The spreadsheet format methodology serves as a blueprint for incorporation into the various WDM database sets populated for the Mooi River Catchment. The inclusion of future research in the catchment thus becomes easy as an existing format exists. The unique number associated with each entry into the WDM databases ensured that the data be sorted based on data type (See Appendix B). Thus, for example, all meteorological stations available for the catchment would be used to populate the WDM database from 1 to 100, water quantity data from 100 to 20 000, etc. On this basis, the data are used in the running of HSPF and ICIS. Thus, instead of having to down load all the required data while running the relevant model, the unique WDM number allows the HSPF program to locate and utilise the data prescribed in the UCI to run the model. Latitude and longitude positions have the advantage of adding a spatial dimension to the data. In this way, both temporal (time) and spatial (space) data are available for the Mooi River Catchment. The added spatial dimension results in more effective visualisation and analyses of the data when incorporated into ICIS. The ICIS system, as mentioned previously, has the ability to formulate real-time, time-series analysis which is particularly useful in the visualisation of results.

5.6 Hydrological simulation of the Mooi River Catchment using the HSPF Model

Simulation of the Mooi River Catchment using HSPF requires the input of meteorological data. Meteorological records of precipitation, estimates of potential evapotranspiration, air temperature, wind, solar radiation, humidity and cloud cover are required for catchment simulation. The meteorological data required were attained primarily from the South African Weather Bureau and Department of Water Affairs and Forestry, although some basic meteorological data were acquired from the gold mines and farmers in the area. The meteorological data are compiled in the WDM along with rest of the data required to run an HSPF simulation.

For simulation with HSPF, the Mooi River Catchment has to be segmented into areas of similar environmental concern. The catchment is, therefore, represented in terms of land segments, reaches and/or well-mixed reservoirs or impoundments. A land segment is a subdivision of the simulated catchment (Hydrocomp, 2000). The boundaries are established according to the user's needs, but generally, a segment is defined as an area with comparable hydrological characteristics. For modelling purposes, water, sediment and water quality constituents leaving the catchment move laterally to a downslope segment or to a reach or reservoir. Spatial variability is produced by dividing the catchment into hydrologically homogeneous land segments and then simulating runoff from each land segment independently, using different meteorological input data and catchment parameters. The Mooi River Catchment was divided into segments based on assistance and advice attained from academics, stakeholders and researchers, working or living in the catchment. Their cumulative knowledge-base of the Mooi River Catchment is high and proved to be an invaluable resource to the study. The segmentation of the river is dependant on the needs of the various users. The segments can be changed and adjusted to suit the scale and extent of the available data, as well as to the experience and understanding of the end user.

Once the catchment was divided into the various land segments, representative cross sectional profiles of the river courses in each of the land segments were required. In order to establish the cross sectional profiles, extensive field investigation and analysis was required. Selecting the locations of the cross sectional profiles was critical as they had to be representative of the land segment. With the aid of a theodolite, ranging rod and field assistants the rhomboid nature of the river course, including the floodplain characteristics and dimensions, were determined. In addition to the river course, the dimensions of the various pipelines and canals were determined. Within the Mooi River Catchment, the pipeline and canal network play a crucial role in retaining the water on the surface and preventing it from being reincorporated in the dolomite. By determining the quantities of water transported in the pipeline and canal system, the calibration of the HSPF model can be attained with a higher degree of certainty within the catchment. The physical measurements and parameters required to describe the land area, channels and impoundments can be output as either printed tables at a given time step, or as a flat file or as the WDM file. It is important to remember, however, that the preprocessing software uses data from the WDM file, as does the GIS discussed in Section 5.7. Thus, storage in the WDM is preferable. In this way, hundreds of computed time series may be selected for the output file (Hydrocomp, 2000).

On the basis of all the data and information collected, a UCI (user control input file) was created using the HSPF software and the HSPF user manual. An example of the UCI for the Wonderfonteinspruit is located in Appendix C. Additional UCI for the Mooi River Catchment can be located at the Computing Centre for Water Research (CCWR). The CCWR currently stores all data and information for the Mooi River Catchment. The data will be housed at the CCWR until the system is functioning independently by the CMA and stakeholders within the Mooi River Catchment. Thereafter, the stakeholders will have to decide where the mainframe system will be housed. The future location of the mainframe system needs to be housed in an unbiased environment such as a university. Within a university environment, an open and transparent process that is flexible and iterative is ensured. This will overcome the barriers of communication between stakeholders which arise from geographic and disciplinary separation leading to adaptive and generative management which will incorporate and reflect the inputs of all stakeholders. The very nature of the university system will also ensure the continual advancement of the EDSS.

Given the complexities of HSPF and the number of tasks it can perform, the manual nature of HSPF can present serious obstacles (Brun, 1998).

The UCI (which informs HSPF of the watershed and land use delineation, meteorological inputs, modules to be used in the model run, watershed and stream network connectivity and model parameters) acts as a format for the inter-connectivity of the Mooi River Catchment and can become intricate. One such complication in the Mooi River Catchment was the division of land segments between cultivated and non-cultivated land as well as land segments on dolomitic and non-dolomitic compartments. The solution came in the form of a three digit code suggested by Prof Johanson (pers comm), one of the HSPF designers. The first digit of the three digit code identified the meteorological station (1 to 7) from which the meteorological data was used, the second digit categorised whether the land segment was cultivated (1) or non-cultivated (2) and the third digit whether the land segment was over dolomite (1) or non-dolomitic (2). Field determination and ground 'truthing' of the various land segments within the catchment play an important role in calibrating the HSPF model.

Once the UCI has been created and the WDM populated with data, the HSPF model can be run to simulate hydrology and water quality in the Mooi River Catchment. Assuming that the UCI structure is correct, hydrographs from simulated and actual data should be closely aligned. This, however, is not usually the case during the first simulation run. Instead, the calibration of the model is required to ensure that simulated and actual data hydrographs tend towards each other and that basal flow measures are similar. Only when the calibration of the simulation run has been attained, is it possible to question future 'what if' scenarios. There are many documents available to assist in the calibration process such as Donigan *et al.* (1984); Lumb *et al.* (1994); Bicknell *et al.* (1997) and Jobes *et al.* (1998). These documents have been put together by experts in the HSPF field to assist users. The calibration of HSPF in the Mooi River Catchment was challenging. Due in part to the pervious nature of the mine dumps and tailings dams prevalent in the catchment and the presence of subsurface dolomite, some of which was dewatered. It is the first time that HSPF has been used on such a complex catchment in South Africa. Although some difficulties and shortcomings were experienced, such as missing rainfall data that needed to be patched and conflicting information from the various stakeholders, HSPF was capable of handling the complex and difficult nature of the Mooi River Catchment.

The calibration of simulated and actual hydrographs allowed for further HSPF simulation within the Mooi River Catchment. Thereafter, water quality constituents were included in the simulated runs and again a calibration of the system was required. The addition of water quality constituents, allows for the mapping and routing of pollutants within the Mooi River Catchment and is an important consideration with respect to environmental management and planning. The future of water quality modelling within the catchment using HSPF still has a long way to go as there is still so many blank areas with little or no data. Hopefully the advent of the EDSS will facilitate the advent of future research and the sharing of applicable data in this regard.

Data requirements are extensive and learning to use the model correctly requires time. However, the model is highly recommended on the basis that it is the most accurate and appropriate management tool available for the continuous simulation of hydrology and water quality in catchments in South Africa to date.

5.7 ArcView GIS and ICIS: their roles in the Mooi River Catchment

Although many studies have been conducted in the Mooi River Catchment, very little GIS data are commercially available. Therefore, in order for the GIS portion of the project to be populated, information from the 1: 50 000 map sheets (available from the Surveyor general in Pretoria) were digitised, cleaned and incorporated initially into ArcView GIS and then into the ICIS. The development of an environmental database for use in the GIS is essential to the environmental planning of the Mooi River Catchment. The GIS is essential to the development of various land use scenarios for the past, present and future (van Riet *et al.*, 1994). Linking of the GIS with the hydrological model HSPF can prove to be important in determining environmental impacts from changes in the catchment.

5.7.1 Digitising of the data

Digitising is the process of converting features from a paper map into digital format through the use of a digitising tablet. At least four points per 1: 50 000 map sheet are required to register the map sheet with ArcView GIS. A root mean square error (RMSE) is calculated by the software which indicates the difference between each measurement and the true value. In order to reduce error, the RMSE is required to remain below 0.025 centimetres, which at the orthophoto scale of 1:10 000 converts to an error of more than 2.5m on the ground. The control points are used to geographically position features digitised, according to the distance from the known points. The digitising process works on the principle of drawing a series of straight lines to represent the true curved line. Digitising is scale-dependent in that the digital representation can never contain greater detail or achieve higher locational accuracy than the original document. The degree of line generalisation which takes place during input is under the subjective control of the operator.

Digitising of data for the Mooi River Catchment was undertaken using a digitising tablet connected to Microstation 95 software and the 1: 50 000 series available for the area. Digitised attributes include towns, roads, rivers, dams, canals, furrows, quaternary catchments, geology, gold mine boundaries, tailing dams and rock dumps, cultivated and non-cultivated land, rainfall stations, temperature stations, altitude and vegetation. The next phase of the process involves projecting the image to match the source data projection.

5.7.2 Map projection

South Africa's standard projection has recently changed to the World Geodetic System, 1984 (WGS84) because of the advancements in modern positioning technologies and the globalisation of techniques and data. Due to its location at Hartebeeshoek outside Johannesburg, the datum is referred to as the Hartebeeshoek 94 datum. However, the projection used in the Mooi River Catchment study varies from the new South African standard system because the base maps used for digitising, were created prior to the systems change. Thus, the previous projection system was used for the Mooi River Catchment.

The former projection system, namely the Gauss Kruger (conform) projection or the Transverse Mercator projection, projects a sphere into a cylinder, tangent to the central meridian. The Transverse Mercator is conformal in that the scale of a map at any point on the map is the same in any direction. Meridians (longitude) and parallels (latitude), therefore, intersect at right angles, shape is preserved locally, and the distortion of area, scale, distance and direction increase away from the central meridians. In order to cover the large east-west extent of the country, South Africa used a number of adjacent Transverse Mercator projections. The projections are centred on every odd meridian with two degree zone widths (one degree on either side of the central meridian) LO27 is the projection used for the Mooi River Catchment as the meridian is centred at 27°E which runs to the west of

Potchefstroom.

5.7.3 Editing of the digitised data

Cleaning and editing of the digitised data for the Mooi River Catchment was undertaken in the software package PC ArcInfo, a powerful data management system. The digitised file was converted to a PC ArcInfo coverage file. Start and end points of each arc, as well as intersections between polygons was identified and manually joined together. A snap tolerance (the process of moving features to coincide exactly with co-ordinates of another feature within a specified distance, or tolerance) was not used to automatically snap arcs together due to the close-set nature of the features digitised. Up until this point, the polygons of each coverage file remain meaningless. It is only when the relevant database is created and assigned various features, that the polygons become meaningful. In order to achieve this, the clean PC ArcInfo coverages, were converted to ArcView GIS shapefiles. The creation and editing of the corresponding tables to include the relevant feature for each polygon in each image was derived using options in ArcView GIS. Inherent errors were minimised through careful data capture and representation eg if polygons were labeled as the incorrect feature, it was corrected by the data (Rivers-Moore, 1997; Woods, 1997).

Ground truthing and field surveys were undertaken to check that the information on the map conformed to the information actually present on the ground. Ground truthing was made easier by the use of a GPS (Global Positioning System) that can pinpoint ones position on the globe through satellites at an accuracy of 5m. Random features and attributes tested while in the field using the GPS were matched to the same point on the digitised map to determine the level of error of the maps. The level of error is important as general assumptions about spatial patterns and trends make for better decisions in management later.

5.7.4 Incorporation of the GIS data into ICIS

After the data have been cleaned and ground truthed, the shapefiles are ready to be included into the ICIS as new coverages representing different features and attributes of the Mooi River Catchment. Each of the coverages represents a different feature for example, geology, towns, rivers. Together the coverages make up a picture of the environmental attributes essential to the environmental planning of the Mooi River Catchment. Linking of the ICIS with the hydrological model HSPF can prove to be important in determining environmental impacts from changes in the catchment.

5.8 Microsoft Access databases as a tool for decision support and their role in the Mooi River Catchment

In addition to the WDM file, a series of Microsoft Access databases were developed and populated to store useful information that did not directly relate to the hydrological model HSPF or the ICIS. This package makes it easy to access required information as well as providing a powerful tool that facilitates in the organisation and sharing of databases in order to make better decisions.

A series of databases was designed using Microsoft Access for the Mooi River Catchment. These included a help database, an address database, a literature database, a meta database, a systems/method database, a legislation or regulation database and a remedial database. As with all database, data can be sorted and queried based on the preference of the researcher. An important factor that needs to be considered with respect to the various database is that they continually need to be updated. The updating of data and information is essential to the environmental planning and management of the Mooi River Catchment and will ultimately become the responsibility of the catchment management authority. At present, the North West Province Department of Tourism, Environment and Conservation is responsible for the continual updating of information. Once the catchment management authority is fully established and has taken over the governance of the Mooi River Catchment, the task will become the responsibility of the authority.

5.9 The empirical study: a guideline

The empirical study of the Mooi River catchment can be viewed on the World Wide Web site http://www.ccwr.ac.za. under the heading - *Other home pages reflected/hosted by the CCWR* or on the disk accompanying the document which is included to illustrate the nature of the empirical study for those people who do not have access to the www. If using the www then click on the Lower Wonderfonteinspruit Forum option. This creates a link to the front page of the Wonderfonteinspruit home page which is illustrated by a locality map of the Mooi River Catchment.

Various topics and identified problems are listed at the bottom of the page. The hypertexted topics are links to the files containing publicly accessible data. These files can be accessed and viewed using the ICIS web browser once it has been downloaded to a local personal computer. Topics that are not currently hypertexted are due either to the sensitive nature of the data or as a result of issues relating to data ownership eg radioactivity. Once such disputes have been settled, these links will become operational. The continual review and development of the Mooi River Catchment ICIS are paramount to ensure constant public access to updated information which can facilitate in the decision making process.

The public domain ICIS software has been customised for the Mooi River Catchment.

The ICIS is made up of two sub-systems namely the GUI and the Systems Manager (SM). The GUI for ICIS is provided by the ArcView GIS system and presents a familiar picture to the user. The SM interprets the commands from the GUI and communicates with the other components of the system implemented in the scripting language of ArcView.

On loading ICIS for the Mooi River Catchment, two options are available on the customised toolbar. The first 'button' pertains to time series data and will be discussed later. The second 'button' accesses the general data available in the system. General data are similar to the normal functionality of ArcView GIS. Thus, various coverages pertaining to the various aspects of the environment are included. These data are digitised and edited before being included in the ICIS system. Operations of the general data component are similar to the functions available in the ArcView GIS in that themes can be added, edited and queries made.

The time series component of the ICIS is more interactive with respect to data and presents a spatial visualisation of the time series perspective. Three options are available on selection of the time series button. The first two options namely yearly and monthly are similar and are discussed together. These options enable data to be viewed at sub-catchment scale. Hydrological simulation using HSPF requires the division of the catchment into sub-catchments. Monthly and yearly inputs and outputs from the model can thus be viewed within the Mooi River Catchment.

Such a display option allows for the viewing of the same variable across all or selected sub-catchments in a particular time step. The data of the specified variable are thus animated. By creating a Catchment-wide plot, more than one year of data can be viewed. In this way, multiple copies can be viewed at the same time.

The base shape selection tool allows for the output from a sub-catchment of river section to be represented. Select the required variable/variables from the box provided and click OK when complete. Another box requiring the period of data to be viewed is presented. If the ICIS is in network mode, then it will ask you if you would like to update the most current data from the mainframe. If, however, you intend using locally stored data, press cancel. If there are data to be transferred, then a data transfer will automatically be initiated using the Automatic Data Acquisition script. The updated data can then be used as outputs from the model.

When the data view is active, the data can be viewed as either an animation, a catchment plot, or a route-trace. The animation option illustrates each step of the time series, with a short pause in between the steps. The catchment plot creates a line plot of all sub-catchments over a number of years within the active window. The route trace option can be used in conjunction with the catchment plot to trace an upstream or downstream selection of the catchment. This feature can be used as a means of identifying potential pollution routes downstream as well as a method to track potential pollution sources upstream. If a route trace is followed directly after a catchment plot, then the catchment plot will show the current sub-catchment selections.

Sometimes, however, a catchment plot is too concentrated and a single sub-catchment plot is required. This can be achieved by selecting the single catchment plot button. When the data are used on a monthly data view, the resultant chart allows for the stepping forward or backwards in time for the length of the data record.

In contrast to the monthly and yearly time series evaluation, the daily time series component allows point source data to be viewed as well as sub-catchment analysis in a daily time step. The point sources include gauging stations, weather stations and monitoring sites. The data are made available in exactly the same manner as in the monthly and yearly plots. Viewing of the data is currently done through one of two external programmes which are linked to the ICIS system. The daily plot can be modified to include sub-catchment data and point data from a list of variables. Again the option of updating the data using the Automatic Remote Data Acquisition script is available.

The future of ICIS in the Mooi River Catchment is dependent on the continual updating and use of the system to facilitate decision making. The ICIS is set up in such a way that the differences in system software do not create a barrier for ICM. In fact the multi-tasking capabilities of ICIS facilitate collaboration rather than competition. Within the Mooi River Catchment a number of external databases have been developed and populated eg literature, metadata, legislative. These data have been connected to the system as a series of help databases to assist in the decision making process. The relationship between the predictive tools (HSPF) and visualisation tools, which display both the observed data and the output of model simulations create an interactive link as a method to better understand the management of environmental resources.

5.10 The future and functionality of an EDSS in the Mooi River Catchment

Although implementation of the EDSS is still in its infancy and is conceived to be a long term commitment, the empirical study undertaken within the Mooi River Catchment illustrates that the development of an EDSS using public domain software for public use is possible as a means of addressing the complex environmental concerns within the catchment.

However, the creation and development of and EDSS using public domain software does raise issues of access, custodianship, control and management rights. In order to clarify some of these issues they need to be discussed in greater detail. Access to and data assimilated with the EDSS is available to all members of the public, including stakeholders and IAP's. Although a broad statement, the philosophy is sound and aligns with the ideals of the ICM approach adopted by South Africa. In addition, such a statement contributes positively towards and identifies goals towards which the EDSS can ultimately strive. At present, access to the EDSS is two pronged. The first level of access is via the Internet. The advantages of which include the fact that the stakeholder or IAP's do not need the software loaded onto the machine in use and can be geographically located in a different area to the stored data. The only technological requirement is access to a computer and the Internet.

This in itself can be problematic in a country such as South Africa, as a vast percentage of the population does not have access to such facilities. However, such a problem should not preclude the use of high-level technology. Instead, measures and procedures should be set in place by the CMA's to facilitate stakeholders and IAP's that need assistance, not only with respects to using the system, but also alleviating their fears and concerns regarding the use of the EDSS to facilitate management of the environment. With time, it is hoped that the measures taken will bridge the gap between high-level technical users, stakeholders and IAP's. The second level of access involves the CMA and IAP's within the catchment area. At this level, all data pertaining to the catchment is located and stored in one centralised location. Users then log onto the system and access data via the centralised storage facility. In addition, the EDSS software can be loaded onto a PC, allowing the user to use the EDSS and analyse data from their own PC without a continual link to the Internet. In this way, new data can be uploaded or downloaded via the Internet connection only as required.

Closely affiliated to the issues of access, are the concerns of custodianship, control and management rights. The EDSS for the Mooi River Catchment belongs to all stakeholders and IAP's. The EDSS is of most use to the CMA that is currently being established in the catchment, and who will ultimately govern the running and management of the system. It is important to note, however, that although the CMA will control and manage the system, it ultimately belongs to the stakeholders and IAP's and it is their responsibility to take an active role in future development of the EDSS.

Although only high-technology end users currently have access to this type of facilities through a computer facility at present, it is important to note that there is, as yet, no inclusive ICM structure in place that can comprehensively handle and integrate all the information required for effective environmental management. The EDSS for the Mooi River Catchment, therefore, provides a means through which integrated environmental structures can begin to be effectively implemented. Over time, the ICM methodologies currently adopted can be replaced by the more integrated nature of the EDSS thereby ensuring a more effective ICM approach. In the same way, stakeholders and IAP's can systematically be trained, becoming more familiar and comfortable with the system over time. Ensuring that stakeholders and IAP's participate and interact with the system, as well as training and development, is the responsibility of the controlling body and CMA.

In conjunction to concerns regarding access to the data, is the issue of why the EDSS is Internet based. The main reason for being able to access the system via the Internet was based on the fact that it would enable anyone to access the system from anywhere in South Africa or the world. Obviously unregistered users will only have limited access to the data to ensure that it does not become corrupted. But access to registered users through a firewall would safeguard the system from corruption without hindering accessibility. Another consideration, is the fact that technology is advancing rapidly at present. The Internet is a powerful tool that can facilitate integrated environmental management. It is important for the EDSS to remain technologically advanced in order to keep up with the advent of current technology and harness the potential power available. What is evident from the development of the system is that the structure of the EDSS caters for the various levels of expertise and needs of the stakeholders. Be it a simplistic photographic representation of the landscape, to a detailed digital elevation model, both levels and scales are available to the different levels of users.

Although many would argue that the approach and design of such a process in South Africa is unrealistic, it is important to realise that the ICM approach adopted by the government is complex. The complexity of the ICM approach and its importance to the South African government and public are strongly reflected in the new Water Act and other legislation pertaining to the environment. All of the new legislation since 1994 has encouraged public participation and the involvement of the stakeholder. On this basis, it was felt that the EDSS should continue in the same vein promoting a holistic approach to environmental management that included important aspects such as accessibility, affordability, co-ownership and compatibility.

The success of the EDSS for the Mooi River Catchment will only conclusively be able to be determined once the current users become more proficient with respects to running the software. However, there have been a number of documented successes thus far. In addition to the HSPF model being populated and a series of simulations achieved for the Wonderfonteinspruit, extreme rainfall events that have caused the monitoring equipment to reach their full measurement limit have been determined using HSPF. From an integrated management perspective such determinations can now be factored into a flood warning system desperately needed in the area. People living alongside the river course can be made aware, through public participation, of the dangers of living so close to the river system. Researchers can prepare worst case scenarios based on the hydraulic response of the river in such instances and management plans can be devised and implemented. Such information could also help to facilitate the management of tailings dams in the region preventing overspilling and wall collapse during the wet season.

As a researcher, the biggest success of the entire project has been the trust that is beginning to develop between the various stakeholders within the catchment. Stakeholders that have in the past not conversed due to a differing of opinion, are now communicating and trying to understand each others perspectives. It is these seemingly small successes that will eventually determine whether the implementation of an EDSS in the Mooi River Catchment is an achievable reality.

CHAPTER SIX

6 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The results of the study have proven that the creation of an interactive, real time environmental decision making support system using public domain software for public use is possible. The EDSS can achieve integrated catchment management. This was achieved through handling the complexity of water resources as well as the factors influencing the resource. The system can be customised and applied in other catchments and is suitable to handle a broad spectrum of applications as proven in the case study. Customisation of the EDSS for river catchments is possible.

The objectives set for the project were fulfilled:

In Chapter Two, objective one was addressed. The scarcity of water and the associated problems in South Africa are highlighted. Water as a resource was discussed and factors affecting the resource were defined. Water users in the Mooi River Catchment were identified and usage discussed.

Chapter Three defined the integrated catchment management approach outlined in objective two. The holistic approach to water management is highlighted and the challenges for integrated catchment management discussed. Integrated catchment management was defined. A review of current approaches to ICM, its historical development in South Africa and growing sustainable catchment management structures identified. A review of the catchment management approach and the ICM process were also given. The legal frameworks and principles for water management and policies pertaining to the New Water Act were highlighted and discussed.

In Chapter Four, the development and design of decision support systems as a tool for the implementation of an interactive, real time environmental decision support system, was determined thus fulfilling the third objective. The origins and historical foundations of decision support systems were highlighted, defined and assessed. Factors contributing to the acceptance of decision support systems were identified. The systems approach and decision support systems approach were discussed with respect to their role in the decision making process. The various models of decision making were reviewed and the scope and use ascertained. A framework analysis was identified. The need for appropriate data support of decision support systems was highlighted. The role of group decision support systems was established. The various components and tools available for environmental decision support systems were identified and discussed. Misconceptions relating to the use of decision support systems were highlighted.

The feasibility of the creation and implementation of an interactive, real time environmental decision support system, by means of a case study, was performed in Chapter Five (Objective Four).

The theoretical frameworks of water as a resource, integrated catchment management and DSS were a forerunner to the creation of an EDSS for the Mooi River catchment. By using public domain software and customising the software for the Mooi River Catchment, reinvention of the wheel and the substantial costs of software engineering design are avoided. Although the use of the software is relatively easy, some level of proficiency is required. The establishment of an EDSS in the Mooi River Catchment case study can provide a basis from which further development and research can be launched throughout South Africa. The Mooi River catchment case study EDSS can be viewed at http://www.ccwr.ac.za or on the disk accompanying the document.

The potential scarcity of the water resource was highlighted in Mooi River Catchment case study through the use of the HSPF model and ICIS. Water users were identified and quantified based on data and information resources available in the system. The gaps in the knowledge-base need to be acknowledged and addressed through full stakeholder participation. The future success of the EDSS in the Mooi River Catchment hinges on stakeholder participation. Approaches to encourage stakeholder participation in the Mooi River catchment needs to be reviewed to ensure the initiation of the ICM approach. Gaps in the knowledge-base will be reduced as the various stakeholders within the Mooi River catchment begin to partake in the ICM process.

The Mooi River Catchment case study highlighted the holistic approach to ICM. In order for HSPF and ICIS to operate, data pertaining to all aspects of the environment are required. The challenges of ICM are demonstrated by the Mooi River Catchment case study. Previous studies in the catchment tended to be very fragmented and piecemeal. Data collection occurred in isolation. The stakeholder's needs focussed on the immediate surroundings rather than on the holistic approach to ICM including imports and exports of the system. Critical success factors of the ICM approach in the Mooi River Catchment are inherently defined in the realisation that a holistic approach is required for catchment management and the implementation of the EDSS. A review of current approaches to ICM enables the Mooi River Catchment case study to learn from historical ICM developments and models. By understanding the historical developments, it is possible to improve on the catchment management structure within the Mooi River Catchment case study.

In the same way, an understanding of the historical developments of DSS can impact positively on the Mooi River Catchment case study EDSS. The need of a systems approach framework lead to the implementation of an EDSS that included, amongst others, the components of the hydrological model, HSPF and the GIS-based software, ICIS. The Mooi River Catchment case study proves that the critical factors identified can be addressed using a DSS. The combined uses of HSPF and ICIS fulfil the criteria of an authentic EDSS.

Used collectively, the various components comprise the EDSS which is operational for the Mooi River Catchment and is available at the site http://www.ccwr.ac.za. The Mooi River EDSS provides an interactive real time series framework to facilitate 'best management practices' to water related problems. The EDSS created represents a new way to structure the involvement of researchers, specialists, stakeholders and managers in environmental management issues. Allowing the most appropriate methodologies, information, people and expertise to be accessed and utilised in river management decision making. Ultimately, the EDSS is not envisaged as a single, large, integrated computer model, but rather a combination of various applicable models or methodologies which would be used within the ICM approach. The output from which would be compatible with input requirements for other information users.

Results from the Mooi River Catchment case study highlight the EDSS's ability to operate within the catchment and provide a means to manage environmental resources. The public domain, hydrological software HSPF, is capable of simulating the continuous, dynamic behaviour of the hydrological regimes and water quality processes of the complex Mooi River Catchment. HSPF is operational and has been calibrated for the Mooi River Catchment. In addition, the WDM supplies a data warehouse facility which provides a systematic approach to the storage and retrieval of vast quantities of data and a means to assimilate and format the extensive data resource available for the catchment while the establishment of an environmental database for use in the ICIS provides a GUI through which spatial time series characteristics of the data can be viewed. External Access databases were developed and populated to facilitate in the management process

The EDSS can thus be used to inform researchers of specific research information requirements, as well as a means to provide agreed protocols for acceptance and incorporation of research information into the decision making process. Protocols need to be formulated to translate broad management information requirements into detailed statements of the issues in question i.e. detailed terms of reference for those activities which must be carried out to provide the necessary information.

In this way, the EDSS facilitates the interaction between managers at different levels, between researchers from various disciplines and between managers and researchers. However, feedback protocols and interaction between managers, researchers and stakeholders at various stages of the decision making process need to still be defined and implemented within the Mooi River Catchment.

The advantages of the implementation of an EDSS for the Mooi River Catchment include involving stakeholders and sharing information to benefit the catchment and advance research. The transparency of the process encourages stakeholders to sit around a table and discuss relevant issues, rather than directing accusations. In this way, research requirements can be identified for the benefit of management within the catchment. The location and storage of all the information in one position is advantageous in that everyone has access to the data, it is not owned by one organisation but rather shared with everyone. Gaps in the knowledge-base can also be highlighted and may take the form of missing data or the identification of further research projects. Ultimately it is important to remember that the system is only as good as the people that use the system and the data stored within the system.

The lack of trust and transparency in the Mooi River Catchment needs to be replaced by one of openness and transparency. The EDSS provides a framework to which the foundations of transparency and trust can be established. By empowering the stakeholders through access to information and the EDSS, environmental problems can be viewed from various perspectives and potential solutions identified.

Most importantly, the implementation of the EDSS in the Mooi River Catchment case study provides a prototype EDSS that can be used as a protocol by CMA for the implementation of ICM around the country. The research successfully documents the development of an EDSS for the Mooi River Catchment using public domain software for public use.

6.2 Recommendations

The following recommendations are derived from the study:

- ❑ Water resources in southern Africa need to be reevaluated in the light of dated studies. It is also important to evaluate the relevance of past studies in the light of current technologies, methodologies and statistics pertaining to both water and human resources.
- ❑ ICM principles and implications of the new Water Act need to be applied in all future ICM initiatives.

- EDSS need to be implemented as a tool for ICM throughout South Africa to facilitate CMA's and stakeholder participation in effective environmental management.

6.2.1 Specific recommendations for the Mooi River Catchment

- Continual research needs to be conducted in the Mooi River Catchment in order to better understand the integrated nature of the environment.
- Develop and implement feedback protocols between managers, researchers and stakeholders at the various stages of the decision making process.
- As new data are collated and synthesised, the present information must be continually updated and used within the EDSS framework.
- Future research should estimate water quality and quantity requirements for the catchment
- Determine the loss of surface water into the dolomitic aquifer.
- Predict and evaluate changes in the river's environments arising from management activities, with appropriate levels of confidence.

References

Acocks, J.P.H (1975) *Veld types of South Africa*. Memoirs of the Botanical Survey of South Africa. **No. 40.** Botanical Research Institute. Department of Agricultural Technical Services. South Africa, Pretoria.

Acocks, J.P.H (1988) *Veld types of South Africa*. Memoirs of the Botanical Survey of South Africa, **57**.

Adriaanse, P.D., Zantinge, D. and Adriaanse, P. (1996) *Data mining*. Addison-Wesley, Reading, Massachusetts.

Adriaanse, M. and Linggaard-Jørgensen, P (1997) Information systems. In Helmer, R. and hespanhol, I (eds) *Water pollution control: a guide to the use of water quality and management principles*. E & FN Spon, London. p 87-123.

AEC (Atomic Energy Corporation) (1995) *Radioactivity analysis of water for the Town Council of Carletonville*. Pretoria, South Africa.

AEC (Atomic Energy Corporation) (1996) *Radioactivity analysis of water for the Blyvooruitzicht Gold Mining Company*. Pretoria, South Africa.

Alexander, W.J.R. (1985) Hydrology of low latitude Southern Hemisphere land masses. In Davis, B.R. and Walmsley, R.D. (eds) Perspectives in Southern Hemisphere Limnology. *Developments in Hydrobiology*, **28**, 75-83.

Alter, S.A. (1975) *A Study of Computer Aided Decision Making in Organisations*. Unpublished Ph.D dissertation. Sloan School, M.I.T.

Alter, S.L. (1976) How effective manager's use information systems. *Harvard Business Review*, **54**, 97-104.

Alter, S.A. (1980) *Decision support systems: current practice and continuing challenges*. Addison-Wesley, Reading, Massachusetts.

Anahory, S. and Murray, D. (1997) *Data warehousing in the real world; a practical guide for building decision support systems*. Addison Wesley Longman, Harlow, UK.

Anselin, L. (1999) Interactive techniques and exploratory spatial data analysis. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 253-266.

Banens, R.J., Blackmore, D.J., Lawrence, B.W., Shafron, M.C., and Sharley, A.J. (1994) A program for the sustainable management of the rivers of the Murray-Darling Basin, Australia. In Uys, M.C. (ed) *Classification of rivers and environmental health indicators*, p 287-300.

Bartone, C., Bernstein, J., Leitmann, J. and Eigen, J. (1994) *Toward environmental strategies for cities: policy consideration for urban development management in developing countries*. UNDP/UNCHS/ World bank, Urban Management Programme, Washington D.C.

Basson, M.S. (1988) *Dolomitic groundwater in the PWV area: integrated systems engineering*. Workshop on dolomitic groundwater of the PWV area. Pretoria, South Africa.

Baxter, J.D. (1983) Line managers move from management information systems to decision support systems for decision-making. In House, W.C. (Ed) *Decision support systems: a data-based, model-orientated, user developed discipline*. Petrocilli, New York.

Bergheim, A and Selmer-Olse, A.R. (1978) River pollution from a large trout farm in Norway. *Aquaculture*, **14**, 267-270.

Bezuidenhout, H. (1988) *'n Plantsosiologiese studie van die Mooirivieropvanggebied, Transvaal*. Unpublished M.Sc thesis, Potchefstroom University for Christian Higher Education, Potchefstroom.

Bezuidenhout, H. (1993) *Syntaxonomy and synecology of Western Transvaal Grasslands.* Unpublished PhD thesis, University of Pretoria, Pretoria.

Bezuidenhout, H. and Bredenkamp, G.J. (1990) A reconnaissance survey of the vegetation of the dolomitic region in the Potchefstroom-Ventersdorp-Randfontein area, South Africa. *Phytocoenologia*, **18**, 387-403.

Bezuidenhout, H. and Bredenkamp, G.J. (1991a) The vegetation of the Bc land type in the western Transvaal Grassland, South Africa. *Phytocoenologia*, **19**, 497-518.

Bezuidenhout, H. and Bredenkamp, G.J. (1991b) Plantegroeiklassifikasie van die A-landtipe van die Mooirivieropvanggebied, Transvaal. *Suid Afrikaanse Tydskrif vir Natuurwetenskap en Tegnologie*, **10**, 4-11.

Bezuidenhout, H. and Bredenkamp, G.J. (1991c) Die plantgemeenskappe van die B-landtipe in die Mooirivieropvanggebied, Transvaal. *Suid Afrikanse Tydskrif vir Natuurwetenskap en Tegnologie*, **10**, 85-92.

Bezuidenhout, H. and Bredenkamp, G.J. (1991d) The vegetation of the Bc land type in the western Transvaal grassland, South Africa. *Phytocoenologia*, **19**, 497-518.

Bezuidenhout, H., Bredenkamp, G.J. and Theron, G.K. (1993a) The vegetation of the Bd and Ea land types in the grassland of the western Transvaal, South Africa. *South African Journal of Botany*, **59**, 319-331.

Bezuidenhout, H., Bredenkamp, G.J. and Theron, G.K. (1993b) The vegetation of the western Transvaal dolomitic and chert grassland, South Africa. In (Bezuidenhout, H.) *Syntaxonomy and synecology of Western Transvaal Grasslands.* Unpublished PhD thesis, University of Pretoria, Pretoria, p 158-185.

Bezuidenhout, H. Bredenkamp, G.J. and Theron, G.K. (1993c) The vegetation of the Ba land type in the western Transvaal Grassland, South Africa. In (Bezuidenhout, H.) *Syntaxonomy and synecology of Western Transvaal Grasslands.* Unpublished PhD thesis, University of Pretoria, Pretoria, p 187-218.

Bezuidenhout, H., Bredenkamp, G.J. and Theron, G.K. (1993d) Phytosociological classes of the western Transvaal grassland, South Africa. In (Bezuidenhout, H.) *Syntaxonomy and synecology of Western Transvaal Grasslands.* Unpublished PhD thesis, University of Pretoria, Pretoria, p 131-156.

Bezuidenhout, H., Bredenkamp, G.J. and Theron, G.K. (1994) Syntaxonomy of the vegetation of the Fb land type in the western Transvaal grassland, South Africa. *South African Journal of Botany*, **60**, 72-81.

Bicknell, B.R., Imhoff, J.C., Kittle, J.L., Donigan, A.S. and Johanson, R.C. (1997) *Hydrologic Simulation Program - Fortran: users manual for Version 11.* EPA/600/R-97/080. US EPA, Ecosystems Research Division, Environmental Research Laboratory, Athens, Georgia.

Bigus, J.P. (1996) *Data mining with neural networks: solving business problems for appliaction development to decision support.* McGraw Hill, New York.

BKS, Stewart Scott and Ninham Shand (1997) *Hydrology of the Middle Vaal Catchment. Vaal River System Analysis Update.* Report No. P 000/00/16496. Department of Water Affairs and Forestry, Pretoria.

Blackmore, D.J. (1995) Murray-Darling Basin Commission: a case study in integrated catchment management. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Blake, T. (1993) *Implementation of the National Water Quality Management Strategy: a discussion paper.* Environmental Protection Authority, Victoria, Australia.

Blanning, R.W. and King, D.R. (1992) Introduction: the growth of decision support. In: Blanning and King (eds) *Current research in decision support technology.* IEEE Computer Society Press, Los Alamentos, California.

Bonczek, R.H., Holsapple, C.W. and Whinston, A. (1981) *Foundations of decision support systems*. Academic Press, London.

Bostrom, R.P., Watson, R.T. and Kinney, S.T. (1992) *Computer augmented teamwork: a guided tour*. Van Reinhold, New York.

Braybooke, B. and Lindblom, C.E. (1970) *A strategy of decisions*. MacMillian, New York.

Bredenkamp, D.B., Botha, L.J. and Venter, D. (1991a) *The flow of dolomitic springs in relation to ground levels and rainfall*. Technical Report GH 3757, DWAF, Directorate of Geohydrology. Pretoria, South Africa.

Bredenkamp, D.B., Fayazi, M. and Botha, L.J. (1991b) *Interpretation of pumping tests in the Gemsbokfontein East Compartment - a typical heterogeneous karst system*. Technical Report GH 3727. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Bredenkamp, D.B. (1995) *Dolomitic groundwater resources of the Republic of South Africa*. Department of Water Affairs and Forestry Report No. GH 3857. Pretoria, South Africa.

Bredenkamp, G.J., Joubert, A.F. and Bezuidenhout, H. (1989) A reconnaissance survey of the vegetation of the plains in the Potchefstroom-Fochville-Parys area. *South African Journal of Botany*, **55**,199-206.

Bredenkamp, G.J., Bezuidenhout, H., Joubert, H. and Naude, C. (1993) The vegetation of the Boskop Dam Nature Reserve, Potchefstroom. In (Bezuidenhout, H.) *Syntaxonomy and synecology of Western Transvaal Grasslands*. Unpublished PhD thesis, University of Pretoria, Pretoria, p 276-297.

Bredenkamp, G. and van Rooyen, N. (1996) Rocky Highveld Grassland. In Low, A.B. and Rebelo, A.G. (eds) *Vegetation of South Africa, Lesotho and Swaziland*. Department of Environmental Affairs and Tourism, Pretoria. p 39.

Breen, C.M, Biggs, H., Dent, M.C. Görgens, A., O'Keeffe, J. and Rogers, K.H. (1995) Designing a research programme to promote river basin management. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Brink, A.B. and Partridge, T.C. (1965) Transvaal karst: some considerations of development and morphology, with special reference to sinkhole subsidence on the Far West Rand. *South African Geographical Journal*, **67**.

Brown, S.A.P. and van Niekerk, A.M. (1995) Strategic approaches to the development and implementation of water quality management plans. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Brun, S (1998) Hydrologic Simulation Program - Fortran (HSP-F). http://www.unc.edu/depts/geog/them/models/hspf/hspfdescription.html (November 2000).

Bui, T.X. (1987) *Co-op: a group decision support system for cooperative multi criteria group decision making*. Springer verlag, Berlin.

Burger, A.J. and Coertze, F.J. (1973) Age determinations - April 1972 to March 1974. *Annals of the Geological Society of South Africa*, **10**, 135-141.

Burger, A.J. and Walraven, F. (1975) Summary of age determinations carried out during the period April 1975 to March 1976. *Annual Geological Survey of South Africa*, **11**, 323-329.

Cheverel, S., Coetzee, H., Denis, L., Prinsloo, J., Lansiart, M. and Maurizot, P. (1998) *Interdisciplinary study of the impact of gold and uranium mining in South Africa*. Council for Geoscience, Geophysics Division. Pretoria, South Africa.

Chittenden, C. (1995) Email. http://www.gaiaconsulting.com.au/articles/email.html (January 2001).

Chorley, R.J. and Haggett, P. (1967) *Integrated models in Geography*. University Paperbacks, Methuen, London.

Chorley, R.J. and Haggett, P. (1969) *Physical and information models in Geography*. University Paperbacks, Methuen, London.

Coetzee, H. (1996) *Pollution of soil and water in the Witwatersrand Goldfields: geophysical evidence and a methodological approach to understanding pollution risks*. Geological Survey of South Africa Open File Report No. 1996-0204. Pretoria, South Africa.

Coetzee, H and Szczesniak, H. (1993) *Detection and monitoring of pollution from mine tailings dams along rivers in the Witwatersrand Goldfield using the airborne radiometric method*. Sixteenth International Colloquium on African Geology, 94-96.

Cole, J.P. and King, C.A.M. (1968) *Qualitative Geography: techniques and theories in Geography*. University Press, Glasgow.

Coleman, D and Khanna, R. (1995) *Groupware: technology and applications*. Prentice-Hall, Englewood Cliffs, New Jersey.

Coertze, F.J., Burger, A.J., Walraven, F., Marlow, A.G. and MacCaskie, D.R. (1978) Field relations and age determinations in the Bushveld Complex. *Transactions of the Geology Society of South Africa*, **81(1)**, 1-12.

Connelly, R.J. (1988) Drilling techniques. *Proceedings: Dolomitic Groundwater of the PWV area*. Groundwater Division of GSSA, Pretoria.

Coppock, J.T. (1962) Electronic data processing in geographic research. *Professional Geography*, **14**, 1-4.

Cornell, A.H. (1980) *The decision makers handbook*. Prentice-Hall, New Jersey.

Council for Scientific and Industrial Research (1969) *Analysis of day/night water sample for DWAF*. Report No. 6848(s)/69. Pretoria, South Africa.

Council for Scientific and Industrial Research (1991) *The situation of waste management and pollution control in South Africa*. Report to the Department of Environmental Affairs by the CISR Programme for the Environment, CSIR, Pretoria. Report CPE 1/91.

Council for Scientific and Industrial Research (1991a) *A situation analysis of water quality in the Mooi River, Western Transvaal*. First Draft Report to Kynoch Fertilisers.

Council for Nuclear Safety (1994a) *Requirements for the control over radioactive effluent discharges and environmental surveillance: mining and mineral processing*. Pretoria, South Africa.

Council for Nuclear Safety (1994b) *Requirements for radioactive waste management mining and minerals processing*. Pretoria, South Africa.

Couclelis, H. (1999) Space, time, geography. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W (eds) *Geographical information systems. Volume 1: principles and issues*. John Wiley and Sons, New York, pages 29-38.

Cowen, C.J. (1988) GIS vs CAD vs DDMS - what are the differences? *Photogrammetric Engineering and Remote Sensing*, **54**, 1551-1554.

Crawford, N.H. and Linsley, R.K. (1966) *Digital simulation in hydrology: Stanford Watershed Model IV*. Department of Civil Engineering, Stanford University. Technical Report 39, 210.

Currie, S.L. (1997) Towards an integrated catchment management plan for the Mdloti River Catchment. Unpublished M.Sc dissertation. University of Natal Pietermaritzburg, South Africa.

Dallas, H.F. and Day, J.A. (1993) *The effect of water quality variables on riverine ecosystems: a review*. Water Research Commission Report No TT 61/93. Pretoria, South Africa.

Davey, G.W., Doeg, T.J. and Blyth, J.D. (1987) Changes in benthic sediment in the Thomson River, southeasten Australia, during construction of the Thomson Dam. *Regulating Rivers*, **1**, 71-84.

Davies, B.R. and Day, J.A. (1986) *The biology and conservation of South Africa's vanishing waters*. Department of Extra-Mural Studies, University of Cape Town, and the Wildlife Society of Southern Africa, Western Cape Branch, Cape Town, p 418.

Davies, B.R., O'Keeffe, J.H. and Snaddon, C.D. (1993a) *A synthesis of the ecological functioning, conservation and management of South African ecosystems*. Water Research Commission Report No TT 62/93. Pretoria, South Africa.

Davies, B.R., Thoms, M., Walker, K.F., O'Keeffe, J.H. and Gore, J.A. (1993b) Dryland Rivers: their ecology, conservation and management. In Calow, P. and Petts, G.E. (eds) *The Rivers Handbook, Volume 2*. Blackwell Scientific Publications, Oxford.

Davies, B.R., O'Keeffe, J.H. and Snaddon, C.D. (1993c) *A synthesis of the ecological functioning, Conservation and Management of South African River Ecosystems*. Water Research Commission Report No TT 62/93. Pretoria, South Africa.

Davis, T.M., Vance, B.D. and Rodgers, J.H. (1988) Productivity responses of periphyton and phytoplankton to bleach-kraft mill effluent. *Aquatic Toxicology*, **12**, 83-106.

Davis, F.D. (1989) Perceive usefulness, perceived ease of use and user acceptance of information technology. *MIS Quarterly*, **13**, 319-342.

de Kock, W.P. (1964) The geology and economic significance of the West Wits Line. *The Geology of some ore deposits of southern Africa. Volume 1.* Geological Society of South Africa, Johannesburg.

Dent, M.C., Lynch, S.D. and Schulze, R.E. (1989) *Mapping mean annual and other rainfall statistics over Southern Africa*. Water Research Commission Report No 109/1/89. Pretoria, South Africa. p 230.

Dent, M.C. (2000) Strategic issues in modelling for integrated water resource management in Southern Africa. *Water SA*, **26(4)**, 513-519.

Department of Environmental Affairs and Tourism (1997) *White Paper on Environmental Management Policy*. Government Printers, Pretoria.

Department van landbou-tegniese dienste (1969) *Verre wesrand dolomiitiese water*. Pretoria, South Africa.

Department of Mineral and Energy Affairs (DMEA) (1989) Explaination of the 1:1 000 000 geological map (4th Edition, 1984) (Compiled by: Visser, D.J.L). *The geology of the Republics of South Africa, Transkei, Bophuthatswana, Venda, Ciskei and the Kingdoms of Lesotho and Swaziland*. Geological Survey, South Africa.

Department of Water Affairs and Forestry (1958) *Beskikking oor water wat uit die skagte van goudmyne in die verre Wes-Rand gepomp word*. Pretoria, South Africa.

Department of Water Affairs and Forestry (1969) *Analysis of West Driefontein water sample*. Report No. 6849(s)/69. Pretoria, South Africa.

Department of Water Affairs and Forestry (1986) *Management of the water resources of the Republic of South Africa*. Department of Water Affairs and Forestry, Pretoria.

Department of Water Affairs and Forestry (1996) *The philosophy and practices of integrated catchment management: implications for water resource management in South Africa*. Water Research Commission Report No TT 81/96. Pretoria, South Africa.

Department of Water Affairs and Forestry (1996a) *Discussion document: water law principles.* Department of Water Affairs and Forestry, Pretoria, South Africa. p 15.

Department of Water Affairs and Forestry (1998) *Mooi River Catchment Management Study: Phase 1 Situational analysis*. Pretoria, South Africa.

Department of Water Affairs and Forestry (2000) *Water Use Authorisation process (individual applications).* Edition 1. Department of Water Affairs and Forestry, Pretoria, South Africa.

de Sanctis, G and Gallupe, R,B. (1987) A foundation for the study of group decision support systems. *Management Science*, **33(5)**.

Dhar, V and Stein, R. (1997) *Intelligent decision support methods*. Prentice-Hall, New Jersey.

Dickson, G. and Powers, R. (1973) MIS project management: myths, options and realities. In McFarlin, W. *et al.* (eds), *Information system administration*. Holt, Reinhart and Winston, New York.

Die Komitee oor gehalte van water aan die verre Wesrand (1971) *Vermoedelike skade deur mynwaters aan diere en gewasse in die Oberholzer bespoeiingsgebied.* Pretoria, South Africa.

Donigan, A.S. (Jr), Imhoff, J.C., Bicknell, B.R., and Kittle, J.L. (Jr) (1984) *Application guide for Hydrological Simulation Program - Fortran (HSPF)*. EPA-600/3-84-065. US EPA, Technology Development and Applications Division, Environmental Research Laboratory, Athens, Georgia.

Dreyfus, H.C and Dreyfus, S.E. (1986) *Mind over machine: the power of human initiation and expertise in the era of the computer*. The Free Press, New York.

Duffus, J.H. (1980) *Environmental toxicology*. Edwards Arnold Publishers, London.

du Toit, A.L. (1921) Underground water in the dolomite area. *The geology of the country surrounding Johannesburg*. **Chapter X**, 32-41.

du Toit, A.L. (1939) *The geology of South Africa* (2nd Edition). Oliver and Boyd, Edinburgh.

Dyer, N. A. (1976) Expected future rainfall over selected parts of South Africa. *South African Journal of Science*, **72**, 237-239.

Egenhofer, M.J. and Kuhn, W. (1999) Interacting with GIS. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition).* Volume 1, p 401-412.

Enderlein, R.E. (1995) Protecting Europe's water resources: policy issues. *Water Science Technology*, **31** (8), 1-8.

Enslin, J.F. and Kriel, J.P. (1967) *The assessment and possible use of the dolomitic groundwater resources of the Far West Rand, Transvaal.* International Conference Water for Peace. Washington, D.C. USA.

Envirolink (1995a) *Environmental Management Programme Report for Western Deep Levels Limited and Elandsrand Gold Mining Company: Document 1.* Anglo American Corporation, Johannesburg, South Africa.

Envirolink (1995b) *Environmental Management Programme Report for Western Deep Levels Limited and Elandsrand Gold Mining Company: Document 3.* Water Research Commission Surface Water Study. Anglo American Corporation, Gold and Uranium Division. Johannesburg, South Africa.

EPA (1996) *Better assessment science integrating point and nonpoint sources.* EPA-823-R-96-001, US EPA, Exposure Assessment Branch, Office of Water, Washington, DC.

EPA (1998) Watershed protection: an introduction. http://www.epa.gov/owow/watershed/index2.html 28 May 2000.

Erasmus, F.J. (1998) *Rehabilitation of gold tailings dams in a dolomitic area*. Department of Mineral and Energy Affairs. Pretoria, South Africa.

Fisher, P.F. (1999) Models of uncertainty. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 191-205.

Fleischer, J.N.E. (1977) *Geohydrologic conditions in the Bank Compartment*. Technical Report No. GH 3615. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Fleischer, J.N.E. (1978) *An analysis of springs in the dolomitic aquifers, South-Western Transvaal, Republic of South Africa*. Technical Report No. GH 3121. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Fleischer, J.N.E. (1979a) *Report on the investigation of the Far West rand dolomite aquifers*. Unpublished report.

Fleischer, J.N.E. (1979b) *Groundwater contamination of a dolomitic aquifer in the Zuurbekom Area, South Western Transvaal, Republic of South Africa*. Technical Report No. GH 3110. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Fleischer, J.N.E. (1979c) *Artificial recharge and pollution aspects in the dolomite aqui9fers, Turffontein Area.* Technical Report No. GH 3109. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Fleischer, J.N.E. (1981a) *The geohydrology of the dolomitic aquifers of the Malmani Subgroup of South Western Transvaal*. Unpublished PhD thesis. University of the Orange Free State, Bloemfontein, South Africa.

Fleischer, J.N.E. (1981b) *The geohydrology of the dolomitic aquifers of the Malmani subgroup in the South-Western Transvaal, Republic of South Africa*. Technical Report No. GH 3169. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Flood, R.L. and Jackson, M.C. (1991) *Creative problem solving: total systems intervention*. Wiley, Chichester.

Fölscher, W.J. and Barnard, R.O. (1969) *Poteksperiment met Wes Driefontein mynwater*. Department Grondkunde en Plantvoeding, Universiteit van Pretoria, South Africa.

Forster, S.F. (1992) Integrated catchment management: justification, feasibility and limitations. *Water Sewage and Effluent*, **12**, 30-34.

Förstner, U and Wittmann, G.T.W. (1981) *Metal pollution in the aquatic environment*. Springer-Verlag, Berlin.

Fourie, J.M. and Görgens, A.H.M. (1977) *Mineralisation studies of the Berg River (1974 to 1976)*. Council for Scientific and Industrial Research. Report No. 334. Pretoria, South Africa.

Funke J.W. (1990) *The water requirements and pollution potential of South African gold and uranium mines*. Water Research Commission Report KV 9/90. Pretoria, South Africa.

Geoffrion, A.M. and Powers, R.F. (1983) Management support systems. In House, W.C. (Ed) *Decision support systems: a data-based, model-orientated, user developed discipline*. Petrocilli, New York.

Geological Survey (1954) *Report on the groundwater in the mining areas of Blyvooruitzicht, West Driefontein, Doornfontein and Venterspost Mines and its relation to the supplies of the Oberholzer and Venterspost Loop Irrigation Boards*. Pretoria, South Africa.

Geological Survey (1967) *The assessment and possible future use of the dolomitic groundwater resource of the Far West Rand, Transvaal, Republic of South Africa*. Technical Report GH 1849. Pretoria, South Africa.

Görgens, A., Pegram, G., Uys, M., Grobicki, A., Loots, L., Tanner, A. and Bengu, R. (1998) *Guidelines for Catchment Management to Achieve Integrated Water Resources Management in South Africa*. Water Research Commission Report KV 108/98.

Gorry, G.A. and Scott Morton, M.S. (1971) A framework for management information systems. *Sloan Management Review*, **13**, 55-70.

Gray, P. and Watson, H.J. (1998) *Decision support in the data warehouse*. Prentice-Hall, New Jersey.

Grobowski, R., McGoff, C., Vogel, D. Martz, B. and Nunamaker, J. (1990) Implementing electronic meeting systems at IBM: leassons leamt and success factors . *MIS Quarterly*, **14(4)**.

Guptill, S.C. (1999) Metadata and data catalogues. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: management issues and applications (2nd Edition)*. Volume 2, p 677-692.

Hammond, E.H. (1964) Analysis of properties in land form Geography: an application to broad-scale land form mapping. *Annals of the Association of American Geographers*, **54**, 11-19.

Henzen, M.R. and Murray, G. (1967) *Notes on the irrigation of West Rand dolomitic waters*. CSIR, National Institute for Water Research. Pretoria, South Africa.

Hogue, J.T. and Watson, H.J. (1983) Managements role in approval and administration of decision support systems. *MIS Quarterly*, **7(2)**, 15-26.

Hollingworth, B and Mullins, D. (1995) Economic analysis of water resource development proposals in the Sabie River basin. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

House, W.C. (1983) *Decision support systems: a data-based, model-orientated, user developed discipline*. Petrocilli, New York.

House, M.A. (1995) Aesthetic pollution and the management of sewage-derived waste. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

http://www.aquaterra.com (November 2000)

Hydrocomp (2000) Hydrological Simulation Program - Fortran (HSPF). http://www.hydrocomp.com/HSPFinfo.html (November 2000).

Interdepartmental committee (1960) *Dolomitic mine water: Far West Rand*. Pretoria, South Africa.

Irving, C.J. (1958) *Some aspects of the water problem in the Blyvooruitzicht - West Driefontein Area.* Rand Mines, Johannesburg, South Africa.

Issar, A. (1994) *Proposal for the study of the regional groundwater flow in South Africa, with reference to the Transvaal and northern Cape dolomite - Special Report*. DWAF, Directorate of Geohydrology. Pretoria, South Africa.

Jelassi, T., Klein, M.R. and Mayon-White, W.M. (1992) *Decision support systems: experiences and expectations*. North-Holland, Amsterdam.

Jennings, J.E. (1965) Building on the dolomites in the Transvaal, Kanthack Memorial Lecture. *The Civil Engineer in South Africa*, **60**.

Jessup, L.M. and Valacich. P.A (1993) *Group support systems: new perspectives*. MacMIllan, New York.

Jobes, T.H., Kittle, J.L. and Bicknell, B.R. (1998) *A guide to using HSPF special actions*. OSV documentation. Aqua Terra, USA.

Johnson, R.J. (1999) Geography and GIS. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W (eds) *Geographical information systems. Volume 1: principles and issues.* John Wiley and Sons, New York.

Jones, G.A., Brierley, S.E. Geldenhuis, S.J.J. and Howard, J.R. (1989) *Research on the contribution of mine dumps to the mineral load in the Vaal barrage.* Water Research Commission Report No. 136/1/89, Pretoria, South Africa.

Jordaan, J.M., Enslin, J.F., Kriel, J.P., Haveman, A.R., Kent, L.E. and Cable, W.H. (1960) *Finale verslag van die tussendepartementele komitee insake dolomitiese mynwater: verre Wes-Rand,* Department of Water Affairs, Pretoria, South Africa.

Keen, P.G.W. and Scott Morton, M.S. (1978) *Decision Support Systems: an organisational perspective.* Addison-Wesley Publishing Company, Reading, Massachusetts.

Keen, P.G.W (1991) *Shaping the future: business design through information technology.* Harvard Business School, Boston, Massachusetts.

Keersmaekers, H. (1966) *Report on analysis of water samples collected from boreholes G90, G91 and G94: Far West Rand.* CSIR, Pretoria, South Africa.

Keersmaekers, H and Aldridge, A.P. (1967) *A study of the quality of dolomitic water in the Far West Rand with special reference to the influence of mine drainage on the formation of sinkhole subsidences and underground water quality.* Report 532. CSIR, National Institute for Water Research. Pretoria, South Africa.

Kelly, S. (1995) *Data warehouse: the route to mass customisation.* John Wiley and Sons, Chichester.

Kent, L.E. (1958) *Interdepartmental Committee on dolomitic waters pumped by mines; Far West Rand, the effects of mining on the quality of the underground water: a preliminary report.* Geological Survey, Pretoria, South Africa.

King, L.C. (1953) Cannons of landscape evolution. *Bulletin of the Geological Society of America*, **64**, 721-752.

Klein, G.A. (1980) Automated aid for the proficient decision maker. *Proceedings of the 1980 IEEE transactions on systems management and cybernetics conference.* p 301-304.

Kleindorfer, P.R., Kunreuther, H.C and Schoemaker, P.J.H. (1993) *Decision science: an integrated perspective.* Cambridge University Press, Cambridge.

Kleywegt, R.J. and Enslin, J.F. (1973) The application of the gravity method of the problem of groun settlement and sinkhole formation in the dolomite of the Far West Rand, South Africa. *Proceedings: IAEG Symposium on sinkholes related to soluble rocks.* Hannover, Deutsche Geselschaft für Erd-und Grundbau, Essen.

Koenig, W. (1998a) *Investigation of environmental impacts of the tailing dams and the pipe-line system at Doornfontein mine.* Practical Report, Martin-Luther University, Halle, Germany.

Koenig, W (1998b) *Gammaspektrometric analysis of activity concentration of nature radionuklides in soil samples in South Africa - Doornfontein.* Practical Report, Martin-Luther University, Halle, Germany.

Kraak, M-J. (1999) Visualising spatial distributions. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition).* Volume 1, p 157-173.

Kraemer, K.L. and King, J.L. (1988) Computer-based systems for cooperative work and group decision making. *ACM Computing Surveys*, **20(2)**.

Kriel, J.P. (1953) *Disposal of water pumped from shafts of gold mines in the Far West Rand.* DWAF, Pretoria, South Africa.

Kriel, J.P. (1958) *Succession of events and factors affecting a policy for the disposal of dolomitic water pumped from mines*. Interdepartmental Committee on the disposal of dolomitic water pumped by mines: Far West Rand Area. Pretoria, South Africa.

Kruger, G.P. (1973) *Konsepte, tegnieke en prosedures vir die globale hulpbronopnameprogram- terrein.* Soils and Irrigation Research Institute. Report No. 154/73/784. Department of Agricultural Technical Services. Republic of South Africa, Pretoria.

Lahlou, M, Shoemaker, S., Choudhury, S., Elmer, R., Hu, A., Manguerra, H. and Parker, A. (1998) *Better assessment science integrating point and nonpoint sources*. EPA-823-R-98-006, US EPA, Exposure Assessment Branch, Office of Water, Washington, DC.

Land Type Survey Staff (1984) *Land types of the maps 2626 West Rand and 2726 Kroonstad*. Memoirs on the Agricultural Natural Resources of South Africa. No. 4.

LaPlante, A. (1993) Liberate your data. *Forbes*, **93**, 55-68.

Larsen, H. and Ipsen, N.H. (1997) Framework for water pollution control. In Helmer, R. and Hespanhol, I. (eds). *Water Pollution Control: a guide to the use of water quality management principles.* E & FN Spon, London. p 275-301.

Larsen, H., Ipsen, N.H. and Ulmgren, L. (1997) Policy and principles. In Helmer, R. and Hespanhol, I. (eds). *Water Pollution Control: a guide to the use of water quality management principles.* E & FN Spon, London. p 1-9.

Laudon, K.C. and Laudon, J.P. (2000) *Essentials of MIS organisation and technology: organisations and technology in the networked environment. 6th Edition*. Prentice-Hall. New Jersey.

Lawrence, P.R. and Lorsch, J.W. (1967) *Organisation and Environment*. Cambridge, Massachusetts: division of research, Harvard Business School.

Lindblom, C.E. (1959) The science of muddling through. *Public Administration Review*, **19**, 155-169.

Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (1999) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 1.25.

Louw. W.J. (1951) An ecological account of the vegetation of the Potchefstroom area, *Memoirs of the Botanical Survey of South Africa*, **40**, 1-128.

Lumb, A.M., McCammon, R.B. and Kittle, J.L., (Jr) (1994) Users manual for an expert system (HSFEXP) for calibration and application of watershed models. *Proceedings of the Fedral Interagency Workshop on Hydrologic Modelling Demands for the 90's,* Fort Collins, Colorado. US Geological Survey Water Resources Investigations Report 93-4018, 4-1 to 4-7.

Maaren, H and Dent, M. (1995) Broadening participation in integrated catchment management for sustainable water resource development. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

MacDonald, I.A.W. and Crawford, R.J.M. (eds) (1988) *Long-term data series relating to southern Africa's Renewable natural resources*. South African National Scientific Programmes Report, 157, CSIR, Pretoria, p 497.

MacVicar, C.N., de Villiers, J.M., Loxton, R.F., Verster, E., Lambrechts, J.J.N., Merryweather, F.R., le Roux, J., van Rooyen, T.H. and Harmse, H.J. von M. (1977) *Soil classification. A binomial system for South Africa*. Science Bulletin 390. Department of Agricultural Technical Services. Republic of South Africa, Pretoria.

Maguire, D.J. (1991) An overview of the definition of GIS. In Maguire, D.J., Goodchild, M.F. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and applications*. Volume 1. p 9-20

Maguire, D.J. (1999) GIS customisation. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 359-369.

Matthews, P.J. (1995) Water Quality Objectives: a tool to ensure environmental protection and wise expenditure. In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Meador, C.L., Guyote, M.J. and Keen, P.G.W. (1984) Setting priorities for DSS development. *MIS Quarterly*, **8**, 117-129.

McColl, R.H.S. and Hughes, H.R. (1981) *The effects of land use on water quality - a review*. Water and Soil Miscellaneous Publication No. 23. Ministry of Works and Development, Wellington, New Zealand. p 2-59.

McHarg, I.L. (1969) *Design with nature*. Natural History Press, New York.

McKee, J.E. and Wolf, H.W. (1963) *Water quality criteria*. The resource Agency of California, 2nd Edition. State Water Quality Control Building, Publication 3A.

McKenny, J.L. and Keen, P.G.W. (1974) How managers minds work. *Harvard Business Review*, **52**, 79-90.

McLeod, Jr., R (1995) *Introduction to the computer-based information system. In Management Information Systems: a study of computer-based information systems*. (6th edition) Prentice Hall International, London, pages 3 - 32.

McPhail, G. (1995) *A preliminary assessment of the risks associated with Dam 3A West Driefontein Gold Mine*. Gordon McPhail and Associates. Johannesburg, South Africa.

Mintzberg, H. (1976) Planning on the left side and managing on the right. *Harvard Business Review*, **54**, 55.

Mooi River Standards Committee (1999) *In-stream water quality objectives for the Mooi River Catchment*. Presented at the Mooi River Catchment Advisory Committee meeting on 03/03/1999.

Morgan, T.J. and Brink, A.B. (1984) *The Far West Rand Dolomites*. International Conference on Groundwater Technology, Johannesburg, South Africa.

NATSURV 4 (1989) *Water and waste-water management in the dairy industry*. Water Research Commission Project No. 145, TT 38/89. Pretoria, South Africa.

NATSURV 7 (1989) *Water and waste-water management in the red meat industry*. Water Research Commission Project No. 145, TT 41/89. Pretoria, South Africa.

NATSURV 9 (1989) *Water and waste-water management in the poultry industry*. Water Research Commission Project No. 145, TT 43/89. Pretoria, South Africa.

NATSURV 10 (1989) *Water and waste-water management in the tanning and leather finishing industry*. Water Research Commission Project No. 145, TT 44/90. Pretoria, South Africa.

Novotny, V. and Chestes, G (1981) Pollution from impervious urban areas. In *Handbook of non-point pollution: sources and engineering management*. Van Nostrand Reinhold Environmental Engineering Series, New York.

NRA (1995) *Tomorrow's Water: water resources development strategy*. National Rivers Authority, South Western Region. London, United Kingdom.

O'Keeffe, J.H. (1986) *The conservation of South African rivers*. South African National Scientific Programmes Report, **131**, CSIR, Pretoria.

O'Keeffe, J.H. (1990) The influence of man. In Allanson, Hart, O'Keeffe and Roberts (eds) *Inland waters of Southern Africa: an ecological perspective*. Kluwer, Dordrecht.

O'Keeffe, J.H., Uys, M. and Bruton, M.N. (1992) Freshwater Systems. In Fuggle, R.F and Rabie, M.A, (eds) *Environmental management in South Africa*. Juta, Cape Town.

O'Keeffe, J.H. King, J. and Eekhout, S. (1994) The characteristics and purposes of river classification. In Uys, M.C. (ed) *Classification of rivers and environmental health indicators*, p 9-17.

Opperman, J.M. (1998) *Die oppervlak impak van h slikdam op die omgewing*. Unpublished Honours dissertation. Potchefstroom University for Christian Higher Education.

Peuquet, D.J. (1999) Time in GIS and geographical databases. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 91-103.

Petitjean, M.O.G. and Davies, B.R. (1988a) Ecological impacts of inter-basin water transfers: some case studies, research requirements and assessment procedures in southern Africa. *South African Journal of Science*, **84**, 819 - 828.

Petitjean, M.O.G. and Davies, B.R. (1988b) *Ecological and environmental impacts of inter-basin water transfers schemes in southern Africa - a review*. Foundation for Research and Development, CSIR, Pretoria.

Pohlandt-Watson, C. and Jones, E. (1990) Historical, analytical and environmental aspects of the cyanide process in South Africa. *ChemSA*, **October**.

Power, D.J. (2001) Decision support systems - web tour. http://dssresources.com/tour, Version 4.1. January 2001.

Pulles, W. (1992) Water pollution: its management and control in the South African mining industry. *Journal of the Mine Ventilation Society of South Africa*, **45**, 17-36.

Pulles, W. (1993) *Mine water quality management reference manual*. Pulles, Howard and De Lange. Sandton, South Africa.

Pulles, W., Heath, R. and Howard, M. (1996) *A manual to assess and manage the impact of gold mining operations on the surface water environment*. Chamber of Mines South Africa and Water Research Commission Report TT 79/96. Pretoria, South Africa.

Quibell, G., van Vliet, H and van der Merwe, W. (1997) Characteristic cause-and-effect relationships in support of catchment water quality management. *Water SA*, **23**, 193-199.

Rabie, M.A. and Day, J.A (1992) Rivers. In Fuggle, R.F. and Rabie, M.A (eds) *Environmental management in South Africa*. Juta, Cape Town.

Rabie, M.A. and Fuggle, R.F. (1992) The rise of environmental concern. In Fuggle, R.F and Rabie, M.A, (eds) *Environmental management in South Africa*. Juta, Cape Town.

Ramsden, H.T. (1985) The status powers and duties of the Rand Water Board a legal history and analysis. Unpublished PhD. University of the Witwatersrand.

Rasmussen, J. (1983) Skills, rules and knowledge: signals, signs, symbols and other distinctions in human performance models. *IEEE transactions on systems management and cybernetics*, **13(3)**, 257-266.

Rhind, B.J. (1988) Personality as a factor in the development of a discipline. *American Cartographer*, **15**, 3277-3289.

Rivers-Moore, N.A. (1997) *The use of geographical information systems to examine the changes in land use patterns in the Midmar Catchment*. Unpublished M.Sc dissertation, University of Natal Pietermaritzburg.

Roberts, C.P.R. (1983) Environmental constraints on water resource developments. *Proceedings of the South African Institute of Civil Engineers*, **1**, 16-23.

Robey, D and Taggart, W. (1982) Human information processing in information and decision support systems. *MIS Quarterly*, **6(2)**, 61-73.

Rogers, K., Roux, D. and Biggs, H. (2000) Challenges for catchment management agencies: lessons from bureaucracies, business and resource management. *Water SA*, **26(4)**, 505-511.

Rutherford, M.C. and Westfall, R.H. (1994) *Biomes of southern Africa: an objective categorization*. Memoirs of the Botanical Survey of South Africa. No. 63.

Safriel, O and Bruton, M.N. (1984) *Aquaculture in South Africa: a cooperative research programme*. South African National Scientific Programmes Report No. 89. Pretoria, South Africa. p 79.

Sauter, V.L. (1985) The effects of experience on information preferences. *Omega International Journal of Management Science*, **13(4)**, 277-284.

Sauter, V. L. (1997) *Decision support systems: an applied managerial approach*. John Wiley and Sons, New York.

Sauter, V.L. and Schofer, J.L (1988) Evolutionary development of DSS: important issues for early phases of design. *Journal of Management Information Systems*, **4(4)**, 77-92.

Schoonbee, H.J., Adendorff, A., de Wet, L.M., de Wet, L.P.D., Fleischer, C.L., van der Merwe, C.G., van Eeden, P.H. and Venter, A.J.A. (1995) *The occurrence and accumulation of selected heavy metals in fresh water ecosystems affected by mine and industrial polluted effluent*. Water Research Committee Report 312/95. Pretoria, South Africa.

Schulze, R.E., Maharaj, M., Lynch, S.D., Howe, B.J. and Melvil-Thomson, B. (1997) *South African Atlas of Agrohydrology and -Climatology*. Water Research Commission Report Number TT 82/96. Pretoria, South Africa. p 171-172.

Scott, J.E. (1995) The measurement of information system effectiveness: evaluating a measuring instrument. *Databases: advances in Information Systems*, **26**, 43-59.

Scott Morton, M.S. (1971) *Management decision systems: computer-based support for decision making.* Division of Research, Graduate School of Business Administration, Harvard University. Boston, Massachusetts.

Simon, H.A. (1975) A Behaviour Model of rational choice. In: Simon, H.A. (ed) *Models of Man*. Wiley, New York. p 241-260.

Simon, H.A. (1977) *The new science of management decision*. Prentice-Hall, New Jersey. p 46.

Simonic, M. (1993) Interpretation of aquifer pollution in the Zuurbekom South-eastern subcompartment. Technical Report GH 3800. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Simonic, M. (1997) *Groundwater pollution next to Slime dam #1: phase 2*. Draft Report for Kloof Gold Mine.

Singh, A.K. and Gaur, J.P. (1989) Algal epilithon and water quality of a stream receiving oil refinery effluent. *Hydrobiol*, **184**, 193-199.

Singh, H.S. (1998) *Data warehousing: concepts, technologies, implementations and management.* Prentice-Hall, New Jersey.

Sironneau, J. (1993) *The Administration of water in France: legal and institutional aspects*. Cyclostyled Report, Ministry of the Environment, Paris, France.

Sironneau, J. (1994) French water sector organisation and national water policy: physical, institutional and legal aspects. *Water Law*, **May**, 97-99.

Sprague, R.H. (1980) A framework for the development of decision support systems. *MIS Quarterly*, **4**, 1-26.

Sprague, R. H. and Carlson, E. D. (1982) *Building Effective Decision Support Systems*. Prentice-Hall Englewood Cliffs, New Jersey.

Sprague, R.H. and Watson, H.J. (1983) Bit by bit: towards decision support systems. In House, W.C. (Ed) *Decision support systems: a data-based, model-orientated, user developed discipline*. Petrocilli, New York.

Srinivasan, A (1985) Alternative measures of system effectiveness: associations and implications. *MIS Quarterly*, **9 (3)**, 243-253.

SRK (1986) *Report on the feasibility of emergency water supply from wells, Gemsbokfontein Compartment*. Report CI 5315/1. Johannesburg, South Africa.

SRK (1989) *Research on the contribution of mine dumps to the mineral pollution load in the Vaal Barrage*. Water Research Commission Report 136/1/89. Pretoria, South Africa.

SRK (1996a) Goldfields of South Africa (Pty) Ltd *Libanon Gold Mine Environmental Management Programme Report*. Report Number 196369/A. May 1996.

SRK (1996b) Goldfields of South Africa (Pty) Ltd *East Driefontein Gold Mine Environmental Management Programme Report*. Report Number 196369/D. May 1996.

SRK (1996c) Goldfields of South Africa (Pty) Ltd *West Driefontein Gold Mine Environmental Management Programme Report*. Report Number 196369/E. May 1996.

Star, J.L., Estes, J.E. and McGwire, K.C. (1997) *Integration of GIS and remote sensing*. Cambridge University Press, New York.

Stoch, E.J. (1968) *Report on some aspects of the problems associated with the use of mine water for irrigation. Welverdiend,* South Africa, Unpublished.

Stoffberg, F.A., Middleton, B.J. and van Zyl, F.C. (1992) The role of intergrated catchment studies in the management of water resources. In *Proceedings: National Water Week*, 17-19 August, CSIR, Pretoria, South Africa.

Sviridov, S and Oliver (1988) *Water Quality Modelling - Volume A: water quality calibration model*. Report No. P C000/00/7086, Vaal River System Analysis. Department of Water Affairs and Forestry, Pretoria.

Szilagyi, A.D. Jr. (1981) *Management and performance*. Goodyear Publishing Co., Santa Monica.

Talec, J.F. (1995) *The French Experience in River Basin Management*. International Office for Water, Cedex, France.

Tankard, A.J., Jackson, M.P.A., Eriksson, K.A., Hobday, D.K., Hunter, D.R. and Minter, W.E.L. (1982) *Crustal Evolution of Southern Africa: 3.8 Billion Years of Earths history*. Springer-Verlag, New York.

Taylor, B.R. and Roff, J.C. (1986) Longterm effects of highway construction on the ecology of a southern Ontario stream. *Environmental Pollution (Series A)*, **40**, 317-344.

Temperley, B.N. (1978) *Applications of basic concepts of geohydrology to particular aquifers and climatic conditions of southern Africa*. Technical report GH 3175. DWAF, Directorate Geohydrology. Pretoria, South Africa.

Thierauf, R.J. (1989) *Group decision support systems for effective decision making: a guide for MIS practitioners and end users*. Quorum Books, New York.

Thomas, P.R. (1995) Integrated approach to River Water Quality Control. In *Proceedings: River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Thoms, M.C. and Walker, K.F. (1992) Sediment transport in a regulated semi-arid river: the Murray, Australia. In Roberts, R.D. and Bothwell, M.L. (Eds) *Aquatic ecosystems in semi-arid regions: implications for resource management*. Environment Canada, National Hydrological Research Institute, 7, 239-250.

Tyson, J.M. (1995) Quo Vadis - Sustainability. In *Proceedings: River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

UNECE (1993) *Protection of water resources and aquatic ecosystems*. Water Series No. 1, ECE/ENVWA/31, United Nations Economic Commission for Europe, New York.

UNECE (1994) *Convention on the protection and use of transboundary watercourses and international lakes*. ECE/ENHS/NONE/1, Geneva, United Nations Economic Commission for Europe, New York.

USGS (1994) Water Resources Application Software: summary of HSPEXP. http://water.usgs.gov/cgi-bin/man_wrdapp?hspexp.html (November 2000).

USGS (1998a) Water Resources Application Software: summary of ANNIE. http://water.usgs.gov/cgi-bin/man_wrdapp?annie.html (November 2000)

USGS (1998b) Water Resources Application Software: summary of WDM. http://water.usgs.gov/cgi-bin/man_wrdapp?wdm.html (July 1998)

USGS (1998c) Water Resources Application Software: summary of IOWDM. http://water.usgs.gov/cgi-bin/man_wrdapp?iowdm.html (November 2000).

USGS (2000) Water resources applications software: summary of HSPF. http://water.usgs.gov/software.html (November 2000).

van Rensburg, H.J. (1995) *Management of southern African aquifers*. Unpublished PhD Thesis. University of the Orange Free State, Bloemfontein, South Africa.

Van Riet, W.F., Van Rensburg, J.D.J., Dryer, R and Slabbert, S. (1994) *Geographical information system (GIS) and the integrated environmental managament (IEM) procedure in the planning and management of water resources.* Water Research Commission Report. Pretoria, South Africa.

van Veelen, M and van Zyl, F.C. (1995) Integrated water quality management: getting people involved in the Jukskei River. In *Proceedings: River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Van Woerkom, J (1968) *Grondkundige aspekte van besproeiing met mynwater op die Oberholzer besproeiingskema.* Department van landbou-tegniese dienste. Pretoria, South Africa.

Van Woerkom, J (1969a) *Wateroplosbare boorgehaltes en pH waardes van grondmonsters afkomstig van die Oberholzer gebied.* Department van landbou-tegniese dienste. Pretoria, South Africa.

Van Woerkom, J (1969b) *Samerattende verslag oor sekere eienskappe van besproeiingswaters afkomstig van die Wes Driefontein myn en van die Bankoog.* Department van landbou-tegniese dienste. Pretoria, South Africa.

Van Wyk and Louw (1993a) *Strategiese waterbenuttingsondersoek Volume 1: Hoofverslag.* Wesrand Streeksdiensteraad, Randfontein, South Africa.

Van Wyk and Louw (1993b) *Strategiese waterbenuttingsondersoek Volume 10: Waterbalans in die Mooirivierstelsel.* Wesrand Streeksdiensteraad, Randfontein, South Africa.

van Zyl, F.C. (1995) Integrated catchment management: is it wishful thinking or can it succeed? In *Proceedings River Basin Management for Sustainable Development*, 15-17 May, Kruger National Park, South Africa.

Vazonyi, A. (1978) Decision support systems: the new technology of decision making. *Interfaces*, **1978**, 72-77.

Vegter, J.R. (1983) *Moontlikhede van stedelike watervoorsiening uit dolomietgesteentes in die bedieningsbebied van die Randwaterraad*. Nommer 3298. Pretoria, South Africa.

Vegter, J.R. (1985) Dolomitic water supplies with special reference to Southern and Western Transvaal. *Proceedings: International Conference on Groundwater Technology*. Johannesburg, South Africa.

Vegter, J.R. and Foster, M.B.J. (1989a) *The hydrology of dolomitic formations in the Southern and Western Transvaal*. International report. DWAF, Pretoria, South Africa.

Vegter, J.R. and Foster, M.B.J. (1989b) *The geohydrology of dolomitic formations in the Southern and Western Transvaal*. Technical Report GH 3643. DWAF, Pretoria, South Africa.

Venter, P.P. (1969) *The problem of underground water in mines*. Symposium on Groundwater in southern Africa. Pretoria, South Africa.

Veregin, H. (1999) Data quality parameters. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 177-189.

Verster, E. (1973) *Konsepte, tegnieke en prosedures vir die globale hulpbronopnameprogram- grond*. Soils and Irrigation Research Institute. Report No. 154/73/784. Department of Agricultural Technical Services. Republic of South Africa, Pretoria.

Vicory, A.H. (1995) Making the case for managing water on a basinwide basis. In Harris, E. (ed) *New World Water 1995*. Sterling Publications Limited, London, p 39 - 41.

Walton, D.G. and Levin, M. (1993) *The identification and verification f polluted areas in the dolomitic aquifer of the PWV area*. Report GEA-1045. Atomic Energy Corporation, Earth and Environment Department. Pretorai, South Africa.

Warford, J.J. (1994) *Environment, health and sustainable development: the role of economic instruments and policies*. Discussion paper for the Director General's Council on the Earth Summit Action Programme for Health and Environment, June 1994, World Health Organisation, Geneva.

Weavind, T.E.F. (1968) *Problems associated with the use of dolomitic irrigation water*. Department of Agricultural Technical Services, Soils Research Institute. Report No. 153/68. Pretoria, South Africa.

Weeks, C.R. (1982) Pollution in urban runoff. In Hart, B.T. (ed) *Water quality managements: monitoring programmes and diffuse runoff.* Water Studies Centre, Chisholm Institute of Technology and Australian Society for Limnology, Melbourne, Australia.

Weibel, R. and Dutton, G. (1999) Generalising spatial data and dealing with multiple representations. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p 125-155.

Welcomme, R.L. (1992) River conservation - future prospects. In Boon, P.J., Calow, P. and Petts, G.E. (eds) *River Conservation and management*. Wiley and Sons, Chichester.

Wells, J.D. (1987) State of the art: the closure and rehabilitation of mining waste impoundments. In *Proceedings of the international conference on mining and industrial waste management*. Johannesburg, South Africa.

Whitlow, (1983) Hydrological implications of land use in Africa, with particular reference to Zimbabwe. *Zimbabwe Agricultural Journal*, **80**, 193 - 212.

Wipplinger, P.E. and Coetzee, H. (1997) *The use of tailings of the Witwatersrand gold mines as building material: a health hazard of national significance*. Council for Geoscience, Mineral Resources Division. Pretoria, South Africa.

Woods,s D.B. (1997) *Siting artificial water points in Mkuze Game Reserve using GIS*. Unpublished M.Sc dissertation, University of Natal Pietermaritzburg.

Worboys, M.F. (1999) Relational databases and beyond. In Longley, P.A., Goodchild, M.F., Maguire, D.J. and Rhind, D.W. (Eds) *Geographical Information Systems: principles and technical issues (2nd Edition)*. Volume 1, p373-384.

Personal communications

Professor R. C. Johanson (1998) Blyvooruitzicht #3 Tailings Dam, Gauteng, South Africa. 5/8/98

APPENDIX A

ENVIRONMENTAL SETTING OF THE MOOI RIVER CATCHMENT

1 Geology of the Far West Rand and Mooi River Catchment

The geology of the Far West Rand area is highly acclaimed and has been extensively researched and documented due primarily to the presence of the rich gold reserves in the area to the south and west of Johannesburg. The gold mines in the region mine some of the richest gold reserves in the world. The gold is predominantly located in the Witwatersrand Supergroup although gold is also mined to a lesser degree in the Ventersdorp Supergroup and the Black Reef Quartzite Formation (SACS, 1980). The Far West Rand region is also geologically notable for its complex system of dolomitic compartments and dykes that at one time comprised the main source of the potable water resource for the city of Johannesburg and the surrounding areas (Ramsden, 1985). These impermeable nephaline syenite dykes are remnants of the Bushveld Igneous Complex, a huge magmatic intrusion situated to the north of the Mooi River Catchment, which was intruded into the surrounding rocks. Another predominant geological controlling factor in the region is the Verdefort Dome to the south east. The Vredefort Dome, a relic meteor impact site, resulted in crustal warping and inversion of the underlying stratigraphy around the impact site. Subsequent erosion and incision by the Vaal River has resulted in the development of the rugged terrain common in the Vredefort Dome area.

The geological stratigraphy of the Mooi River catchment is summarised in Table 1.1 and illustrated in ICIS on the site http://www.ccwr.ac.za.

2 Topography

The topography of the Mooi River Catchment is strongly influence by the Witwatersrand ridge in the north east, the Bushveld Igneous Complex and Magaliesberg quartzite ridge to the North and the Vredefort Dome to the south. The Witwatersrand ridge forms the drainage boundary between the Vaal River to the south and the Crocodile River to the north. The terrain of the Mooi River Catchment is relatively flat with elevations ranging from 1740 m above mean sea level in the north east of the catchment to 1320 m above mean seal level in the vicinity of the confluence with the Vaal River. The topography within the Mooi River catchment is dominated by the Gatsrand, a ridge of low lying, steep sided, rocky, east-west tending hills which form the drainage boundary between the Loopspruit to the south and the Wonderfonteinspruit to the north. Altitude depicting the topography and influence of the Witwatersrand ridge and the Gatsrand are illustrated in ICIS on the site http://www.ccwr.ac.za. Elevations decrease with increased distance away from the Gatsrand, the topography of the Mooi River Catchment becomes more flat and undulating.

The natural topography of the Wonderfonteinspruit has been drastically altered in its upper reaches due to gold mining in the area. The main impact on the topography is the physical presence of tailings' dams, rock dumps and surface infrastructures. Rock dumps and tailings dam height's range from ± 20 m to ± 99 m, thereby creating a noticeable change in the otherwise flat undulating topography. The formation and presence of sinkholes have also altered the natural topography of the Mooi River Catchment.

3 Climate of the Mooi River Catchment

The Mooi River Catchment is situated in the Highveld climatic zone of southern Africa. Features of the Highveld climatic zone representative of the Mooi River Catchment include a warm temperate climate with warm to hot summers from November to February, and warm sunny winter days with frosty nights. Average annual precipitation ranges

Table 1.1: Generalised stratigraphy of the Mooi River Catchment (DMEA, 1989; Tankard, 1982)

Supergroup / Sequence	Group	Subgroup / Formation	Mean Maximum thickness (m)	Lithology	Age	
					Approximate Years	Period
Alluvium						Quaternary
Karoo	Ecca	Ecca Shale Formation	400	Dark grey shales; siltstones; subordinate sandstone	280 ka	Permian
		Dwyka	> 1000 variable	Diamictite; subordinate varved shale and boulder shale	350 ka	Permo-Carboniferous
Transvaal Sequence	Rooiberg	Schrikkloof	>3000	Ash-flow tuff Fine-grained, flow banded, porphyritic and spherulitic felsites sand stone lenses Shaly and tuffaceous beds Volcanic breccia and agglomerate		Vaalian
		Kwaggasnek	0-3000	Locally flow-folded at top Zone of quartzite xenoliths Zone of amygdaloidal felsite Massive felsite, porphyritic, fine grained and recrystallised in portions		Vaalian
	Pretoria	Rayton				Vaalian
		Magaliesberg Quartzite	0-15	Quartzite		Vaalian
		Silverton Shale	300 min	Hornfels and graphitic shale		Vaalian
		Daspoort Quartzite	190	Orthoquartzite Shale and siltstone Orthoquartzite		Vaalian
		Strubenkop Shale	130	Iron-rich shale and siltstone Conglomerate		Vaalian
		Hekpoort Andesite	280	Amygdaloidal andesitic lava	2224 ± 21 Ma (Burger and Coertze, 1973-1974: 137)	Vaalian
		Timeball Hill	570	Shale Quartzite Shale and siltstone		Vaalian
		Rooihoogte	50	Quartzite Shale Bevets Conglomerate member		Vaalian

	Chuniespoort	Penge		320	Iron formation		Vaalian
		Malmani	Frisco	30	Chert-free dolomite		Vaalian
			Eccles	490	Chert-rich dolomite		Vaalian
			Lyttelton	290	Chert-free dolomite		Vaalian
			Monte Christo	740	Chert-rich dolomite		Valian
			Oaktree	330	Dark coloured dolomite		Vaalian
		Black Reef Quartzite		25	Feldspathic quartzite and shale grading into a conglomerate at the base	2318 ± 17 Ma (Burger and Coertze, 1973-1974: 137	Vaalian
	Buffelsfontein	Tygerkloof Quartzite		± 50	Light coloured orthoquartzite with conglomerate lenses and greywakes		Vaalian
		Witfonteinrant		max 850	Pink rhyolite, quartz and feldspar porphyry, other volcanic rocks and intercalated sediments		Vaalian
		Waterval		± 200	Basic volcanic rocks		
		Hampton		max 600	Immature, volcaniclastic arenite and greywacke with an arkose-shale unit grading into a mature arenite unit at the base		Vaalian
	Groblersdal	Bloempoort		± 3000	Andesite, blue and yellow banded slate, impure quartzite and shale		Vaalian
		Dennilton			Acid lava, tuff, granulitic schist and gneiss	2440 ± 120 Ma (Coertze et al., 1978:8)	Vaalian
Ventersdorp	Pniel Sequence	Allanridge Andesite		743	Green-grey, grey amygdaloidal lava	2460 ± 120 Ma (Coertze et al., 1978:8)	Randian
		Bothaville		388	Agglomerate/ volcanic breccia conglomerate at the base and top of the unit enclosing a sand-grade subgreywacke to subarkosic sediment		Randian
	Platberg	Rietgat		927	Pale green-grey porphyritic lavas at the base of the unit followed by a greywacke sandstone conglomerate and impure lacustrine limestones with algal stromatolites		Randian
		Makwassie		364	Quartz porphyry and associated intermediate lavas and greywacke conglomerate	2638 ± 105 Ma (van Niekerk and Burger, 1968)	Randian
		Kameeldoorns		555	Rounded clasts of volcanics confined to fault troughs that fines rapidly from away from a greywacke boulder conglomerate		Randian

			Edenville	568	Greenchalcedony and clusters of milky quartz amygdales		Randian
			Loraine	217	Variolitic and spherulitic structures surrounded by whitish groundmass hence 'altered zones'		Randian
			Jeannette Agglomerate	97	Prominent thick agglomerate at top. Many agglomerate beds in contrast		Randian
	Klipriviersberg		Orkney	480	Purple-topped ash-flow tuffs		Randian
			Alberton	171	Porphyritic lavas including 'porphyritic marker'		Randian
			Westonaria		Dark green andesitic 'talcose tuffs' and lavas		Randian
Witwatersrand	Central Rand	Turffontein	Mondeor Conglomerate	450	irregular, interrupted conglomerate		Randian
			Elsburg Quartzite	500	Siliceous, grey quartzite at the base followed by speckled, coarse, gritty and argillaceous quartzite		Randian
			Kimberley Conglomerate	300	Quartzite conglomerate		Randian
			Doornkop Quartzite	30	Yellowish-grey argillaceous quartzite		Randian
		Johannesburg	Booysens Shale	150	Shale unit that divides the overlying and underlying quartz units		Randian
			Krugersdorp Quartzite	200	Grey quartzite that contains Bird Reef marker		Randian
			Bird Conglomerate		Quartzitic conglomerate		Randian
			Luipardsvlei Quartzite	300	Grey quartzite		Randian
			Livingstone Conglomerate	20	Quartzitic conglomerate		Randian
			Randfontein Quartzite	200	Grey quartzite		Randian
			Johnstone Conglomerate	25	Quartzitic conglomerate. Combines northwards with the Livingstone conglomerate		Randian
			Langlaagte Quartzite	250	Alternating dull, dark greenish-grey quartzites with light-grey siliceous beds		Randian
			Main Conglomerate	25	Quartzitic conglomerate		Randian
			Maraisburg Quartzite	50	Quartzite unit extending from the base of the Red Bar to the first overlying conglomerate		Randian
	West Rand	Jeppestown	Roodepoort	450	Alternating shale with shaly to very fine-grained quartzite		Randian
			Crown	250	Amygdaloidal lava		Randian

			Florida Quartzite	300	Quartzite unit with a basal small-pebble conglomerate		Randian
		Government	Witpoortjie	865-1590	Alternating green-black magnetic shales, green silty shales and siltstones, and argillaceous to gritty quartzites		Randian
			Coronation Shale	140-180	Prominent black, magnetic shale used as a marker		Randian
			Promise Quartzite	470-750	A sericitic to argillaceous quartzitic unit that contains grit and pebble beds		Randian
		Hospital Hill	Brixton	690	Alternating orthoquartzites with fuchsite and ferruginous shales		Randian
			Parktown Shale	<700	Predominantly shale unit with two informal beds within namely the ripple-marked quartzite and the speckled bed		Randian
			Orange Grove Quartzite	200	Two prominent quartzites seperated by subordinate schistose shale		Randian
	Dominion		Syferfontein Porphyry	1550	Medium-grained porphyry (300 m) Silicified porphyry (500 m) Medium-grained porphyry (750 m)		Randian
			Rhenosterspruit Andesite	730	Green and grey andesitic lavas with subordinate tuffs in the upper 150 m	2 800 ± 60 to 2 830 ± 110 Ma (van Niekerk and Burger, 1969)	Randian
			Rhenosterhoek Quartzite	60	Grey quartzite, yelleow sericitic quartzite and conglomerate bands		Randian
	Archean Granite					2 900 ± 150 Ma (Niclaysen et al., 1962)	Swazian

between 900 mm in the east to approximately 650 mm in the west. Rainfall is generally in the form of showers and thunderstorms and falls mainly in summer from October to March, winter months are usually dry. On average 75 storms occur per year, rainfall during these thunderstorms can be of high intensity with lightening and strong gusty south-westerly winds. Occasionally heavy rainfall events of 125 mm to 150 mm transpire in short periods of time (a couple of hours) due to intensive thunderstorms or cloud bursts resulting in floods and cause extensive environmental, economic and social damage. Hail frequency is high with between 4 to 7 occurrences per season. Summer average daily temperatures tend to range from 17 to 27°C with extreme maxima of 38°C, while winter average daily temperatures range from 0 to 13°C with extreme minima of -13°C. Frost occurs for approximately 120 days from May to September; and prevailing winds are light north-easterly and south westerly, except during thunderstorms when strong gusty south-westerly winds are prevalent.

3.1 Precipitation

Rainfall data from the Potchefstroom, Carletonville and Krugersdorp Weather Stations are presented in Table 3.1. The average annual precipitation in the Mooi River Catchment ranges from 631 mm per annum around Potchefstroom in the south west, to 646 mm per annum at Carletonville and increases to 736 mm per annum measured at Krugersdorp in the north east. Rain generally occurs in summer from October to April with the majority of rainfall in January. Precipitation in the Mooi River Catchment tends to occur as a result of high intensity thunderstorms. Table 3.1 depicts the average number of days of thunderstorms, hail, snow and fog at Potchefstroom, Carletonville and Krugersdorp Weather Stations. Occasionally thunderstorms are accompanied by hail, while snow and fog are more common in the winter months from May to August.

Table 3.1: Average number of days of thunderstorms, hail, snow and fog at the Potchefstroom, Carletonville and Krugersdorp Weather Stations.

Month	Potchefstroom				Carletonville				Krugersdorp			
	Thunder storms	Hail	Snow	Fog	Thunder storms	Hail	Snow	Fog	Thunder storms	Hail	Snow	Fog
January	13	0.4	0	0.1	4.4	0	0	0	5.2	0.3	0	0.2
February	8.7	0.2	0	0	2.7	0.1	0	0.2	4	0	0	0.8
March	8	0.1	0.1	0.5	2	0	0	0.2	3	0	0	1.4
April	4.5	0.1	0	1	2	0	0	0.2	1.5	0.1	0	0.7
May	1.4	0	0	0.9	0.2	0	0	0.9	0.5	0	0	0.3
June	0.4	0	0.1	1.3	0.2	0	0.2	3.2	0.2	0	0.2	0.3
July	0.6	0	0.2	1.4	0.1	0	0.1	2	0.1	0	0.1	0.4
August	1.3	0.1	0	0.3	0.3	0.1	0	0.6	0.3	0	0	0.8
September	2.5	0.1	0	0.3	1.1	0	0	0.2	1	0.1	0	0.6
October	7.7	0.4	0	0.1	3.1	0.2	0	0	2.9	0.4	0	0.7
November	11.3	0.5	0.1	0.2	3.9	0	0	0	3.4	0.3	0	0.8
December	12.5	0.3	0	0.2	4.2	0.1	0	0	4.5	0.3	0	0.4
Annual	72	3	1	6	24	1	0	8	27	2	0	7

Data obtained from records of: Potchefstroom Weather Station 1961 to 1990
Carletonville Weather Station 1961 to 1990
Krugersdorp Weather Station 1961 to 1990

The highest monthly maximum recorded in the Mooi River Catchment is 440 mm (January 1978) at the Krugersdorp Weather Station, followed by 272 mm (January 1974) at the Carletonville Weather Station and 258 mm (January 1976) at the Potchefstroom Weather Station, with the lowest recorded values of 0 mm occurring during the winter months. Maximum rainfall at Potchefstroom Weather Station over 24 hours occurred in January 1977 when 95 mm of rain was computed. This value is slightly lower than those of the Carletonville Weather Station and the Krugersdorp Weather Station where values of 159 mm (December 1976) and 116 mm (January 1978) are recorded respectively. Other maximum rainfall events include 111 mm in February 1966 and 102 mm in October 1969 at the Carletonville Weather Station and 112 mm in May 1976 and 104 mm in March 1976 at the Krugersdorp Weather Station. Extreme rainfall events tend to be highly erosive, this coupled with the highly erodible composition of tailings dams and soils common in the Mooi River Catchment have huge potential implications with regards catchment management.

Implications of such extreme rainfall events in the Mooi River Catchment include flooding of the low-lying areas close to the river coarse by flood waters and the associated resettlement aid for flood victims. Addition environmental implications comprise nitrification of the river course and impoundments and water pollution from point and non-point sources. Corrosion and possible failure of tailings dams as well as soil erosion from agricultural lands and diamondiferous diggings result in high turbidity, suspended solids and siltation of rivers and impoundments of the Mooi River catchment such as the Klerkskraal, Klipdrift and Boskop Dams. Such extreme events, although infrequent, play an important role in flood management in the Mooi River Catchment.

3.2 Temperature and evaporation

Maximum temperatures range from 29.2°C in summer to 18.6°C in winter, while minimum temperatures range from 16.0°C to 0.5°C at the Potchefstroom Weather Station. Temperatures at the Carletonville and Krugersdorp Weather Stations differ slightly in that the temperatures are slightly lower. Maximum temperatures at Carletonville range from 27.8°C to 17.8°C and minimum temperatures from 15.4°C to -0.4°C, compared to maximum temperatures at Krugersdorp which range from 26.1°C to 16.3°C and minimum temperatures from 14.6°C to 2.4°C. Temperatures in the Mooi River catchment are generally warm to hot with mild night temperatures in summer and warm with cold night temperatures in winter. The mean daily temperature ranges from 25.1°C at Potchefstroom to 23.9°C at Carletonville and 22.2°C at Krugersdorp. The highest temperatures recorded in the Mooi River Catchment are 38.6°C (January 1973) at the Potchefstroom Weather Station, 37.1°C (January 1973 and February 1983) at the Carletonville and Potchefstroom Weather Stations respectively and 36.8°C (November 1981) at the Potchefstroom Weather Station. Lowest temperatures recorded include -9.5°C (August 1972) at Carletonville and -9.3 (July 1966) at the Potchefstroom Weather Station. As a result of the low temperatures during the winter months, frost is common for about 120 days between May and September.

Potential A-Pan evaporation figures recorded for the area are high and indicate that the Mooi River catchment is a water deficit area. The average A-Pan potential evaporation for the Mooi River Catchment is 2140.7 mm.

3.3 Wind

Wind patterns in the Mooi River Catchment are generally mild and tend to blow in a north-easterly and south-westerly direction. However, short-lived, gusty winds often accompany thunderstorms. Wind speeds for Potchefstroom and Carletonville Weather Stations are depicted below in Table 3.2

Table 3.2: Wind speed (m/s) at Potchefstroom Weather Station

Site	Direction							
	N	NE	E	SE	S	SW	W	NW
Potchefstroom Weather Station	3.2	3.2	3.3	3	3.2	3.4	3.3	3.5

Weather Bureau data are based on 3 observations over a 29 year period (1959-1988)

4 Water

4.1 Surface drainage

The Mooi River Catchment, a tributary of the Middle Vaal River Catchment (DWAF, 1998), comprises three rivers namely the Mooi River, the Wonderfonteinspruit and the Loopspruit. The Wonderfonteinspruit originates at a height of 1740 m above mean sea level south of Krugersdorp at the Tudor Dam and flows in a south west direction to the Donaldson Dam at a gradient of approximately 0.76%. From the Donaldson Dam, the Wonderfonteinspruit flows easterly past the gold mining towns of Westonaria, Carletonville and Welverdiend. The natural drainage of the Wonderfonteinspruit has been dramatically altered due to the dewatering of the underground dolomitic compartments by the gold mines and the redirection of water. Water that is pumped to the surface is channelled on the land surface in a series of canals and pipelines to prevent the water from percolating back into the underlying dolomite compartments. Dewatering results in surface instability and the creation of sinkholes. The drainage pattern of the Wonderfonteinspruit is characteristic of drainage patterns in karst environments. Additional water is fed into the Wonderfonteinspruit via the Turffontein 'Eye', a natural spring from the underlying dolomitic geology.

The origins of the Loopspruit rise to the south of East Village on the East Driefontein Gold Mine at an altitude of 1700 m above mean sea level. The Loopspruit is comprised primary of furrows, thus having the effect of channelling the water to the south of the Gatsrand. The Loopspruit flows in a south westerly direction towards the Klipdrif Dam. The drainage pattern of the Loopspruit is dendtritic due to the underlying geology and converges with the Mooi River approximately two kilometres downstream from Potchefstroom.

The headwaters of the Mooi River rise at an altitude of approximately 1650 m above mean sea level near the town of Derby in the North West Province and flows in a southerly direction through the Klerkskraal Dam. The drainage pattern of the Mooi River in its upper reaches is classic dendritic. This pattern alters substantially when the Mooi River flows over dolomite. The tributaries flowing into the main river channel are drastically reduced. The geomorphology of the river channel downstream of the Klerkskraal Dam is altered due to diamondiferous gravel diggings in the river channel and flood water areas. This has the result of altering the channel course, widening and deepening the river channel, removing the natural riparian vegetation in and alongside the river course and increasing sedimentation of the water (Currie, 1997). The Mooi River converges with the Wonderfonteinspruit upstream of the Boskop Dam and flows through a series of well developed wetland systems. Water from the Mooi River is used extensively for irrigation of crops and watering of animals in the area via furrows and canals. Convergence with the Wonderfonteinspruit reduces the water quality due to the influences of the gold mines in the Carletonville area. The Gerhardminnebron Eye, situated below the Boskop Dam, flows into the Mooi River.

The drainage of the entire Mooi River catchment has been drastically altered by various pipelines and canals used for irrigation. Due to the low gradient and flat nature of the area, wetland systems are common. These wetland systems are important ecological systems that need to be protected and preserved.

4.2 Surface hydrology

Natural surface waters of the Mooi River catchment are confined to the river channels of the Mooi River, the Wonderfonteinspruit and the Loopspruit. Human disturbance over the years, since 1894, has impacted on the natural system. Early intervention included the supply of one million gallons (4546 Ml) of water per day to the developing town of Johannesburg (Ramsden, 1985). More recent intrusions have arisen through the development of impoundments as storage facilities due to urbanisation and a series of canals and pipelines as a result of the extensive gold mining in the area and the dolomitic substrate. The impoundments of the Mooi River Catchment include the Klipdrift Dam on the Loopspruit tributary, the Donaldson and Carletonville Dams on the Wonderfonteinspruit tributary and the Klerkskraal, Boskop and Lakeside Dams on the Mooi River tributary.

In addition to the large number of impoundments and dams, an extensive canal and pipeline network extends throughout the system. This network of canals and pipelines transport and divert water over the underlying dolomitic compartments. Thereby preventing the surface water from upstream percolating through the substrate and recharging the groundwater in the Malmani Subgroup dolomitic compartments. Further downstream between the Klerkskraal and Boskop Dams and downstream of Potchefstroom a series of furrows and canals have been developed to facilitate in the irrigation of crops. There are various operational irrigation boards within the catchment which are detailed below in Table 4.1.

Table 4.1: Operational irrigation schemes within the Mooi River catchment

River catchment	Irrigation scheme	Dam from which water is used
Wonderfonteinspruit	Oberholzer Irrigation Board	Fissure water from West Driefontein Gold Mine (soon to be disbanded)
Loopspruit	Klipdrift Irrigation Board	Klipdrift Dam
	Vyfhoek South Irrigation Board	Klipdrift Dam
Mooi River	Mooi River State Water Scheme (Vyfhoek North)	Klerkskraal Dam, Boskop Dam, Lakeside Dam and Gerhardminnebron Eye

Prior to mining, water in the riverbed was limited to seepage from groundwater springs and runoff from thunderstorms and rainfall events. To avoid the dolomitic substrate from filling up with water, a surface water conveyance system was constructed to transport water over the dolomitic compartments. One of the main features of this system is the 1 m pipeline which conveys water over the Gemsbokfontein, Venterspost, Bank and Oberholzer dolomitic compartments. Outflow from the Donaldson Dam and surface runoff from the urban area of Bekkersdal are fed initially into a 700 mm diameter pipeline, known as the Venterspost pipe. The Venterspost pipe carries water over the Gemsbokfontein compartment and is discharged into an open flume located on the Gemsbokfontein dyke. The water then flows into the 1 m pipeline. The 1 m pipeline is a 26 km pipe that transports the water across the Venterspost, Bank and Oberholzer dolomitic compartments. The pipe was constructed in the early 1970's by the Far West Rand Dolomitic Water association and is owned by Libanon Gold Mine (20%) and Driefontein Consolidated Gold Mine (80%). From the 1 m pipeline, the water is returned to the Wonderfontein Spruit streambed via a series of canals.

There are approximately 25 flow gauging stations located within the Mooi River catchment. Of which approximately 50% are closed or have no data. The majority of the remaining operational station are located on the Wonderfonteinspruit. Hydrological analysis thus becomes restricted due to the lack of reliable gauges.

4.3 Geohydrology

Dolomite is the most important hydrogeological unit in the Mooi River Catchment, which give rise to some of the most important and well documented aquifers in South Africa. The Mooi River Catchment region is dissected by dolerite dykes which create major structural features defining discrete subsurface compartments. The formations of the Malmani dolomites are of two distinct lithologies namely chert free and chert rich The chert-poor units form massive dolomite bodies as opposed to alternating sequences of dolomite and chert in chert-rich environments. The resistant chert supports large voids resulting from carbonate dissolution (Foster, 1988) and creates zones of preferential weathering which are of significance in the study of contaminant transport and recharge. On this basis, extensive groundwater resources are available which were used to supply the developing city of Johannesburg and surrounds with potable water.

Understanding the surface water - groundwater relationship therefore becomes important in dolomitic compartments. In fact, in order to be able to quantify the relationship in detail, a good surface water flow record, ground water level and abstraction flow records are required. Groundwater influx from surface streams and rainfall represents sources of recharges. However, groundwater may also discharge to surface streams as base flow. Although these two recharge processes may alternate within the same positions in relation to seasonal rainfall variations, the best method of quantifying these relationships in detail is through the use of a hydrological model.

5 Soils

The South African landscape is divided into different land types based on the uniformity of terrain form, soil pattern and climate (Land Type Survey Staff, 1984). The different land types are devised through the collection of all existing information, maps and satellite imagery relevant to the terrain, soils and climate of the 1:250 000 area.

Through a process of field investigation, terrain types (each displaying a marked uniformity of terrain form) were delineated. A terrain unit can be defined as any part of the land surface with homogenous form and slope and comprises the following terrain units namely, crest, scarp, midslope, footslope and valley bottom or flood plain (Kruger, 1973; Hammond, 1964 and King, 1953). The soils within each terrain type were then identified. Soils do not tend to occur randomly in a landscape, but instead follow a pattern determined by factors such as geology and topographic position. This inter-relationship between soils and the land form, comprise the rationale for relating soils to the landscape position in which they occur, and the terrain type provides a suitable framework (Verster, 1973 and MacVicar et al., 1977). These areas, known as pedosystems, are therefore uniform with regards terrain and soil patterns (Land Type Survey Staff, 1984). Climatic zones were then demarcated using climatic boundaries indicators such as natural vegetation, soils, crop performance, altitude and topography (MacVicar *et al.*, 1977). These climatic zones were then superimposed on the pedosystem maps to derive the land type map (Land Type Survey Staff, 1984).

Land type units within the Mooi River Catchment are quite varied due to the underlying geology and include units Ab, Ae, Ba, Bb, Bc, Bd, Fa, Fb and Ib. Each unit is discussed in greater detail below.

5.1 A land type

The A land type map unit, as defined by the Department of Agriculture, is characterised by red-yellow apedal, freely drained soils devoid of water tables which does not qualify as a plinthic catena, occupies at least 40% of the area and belong to one or more of the following soil forms, namely, Inanda, Kranskop, Magwa, Hutton, Griffin and Clovelly. In the Ab land type, the yellow soils occupy less than 10% of the area, whilst dystrophic and or mesotrophic soils occupy a larger area than high base status red-yellow apedal soils. Soils of the Ae land type unit differ from the Ab land type in that it is deeper than 300 mm and no dunes are present. However, both of these units have red apedal soils. The dominant soil form is Hutton

(90% of the land type) and less than 6% of the soils of the A land type are Glenrosa and Mispah soil forms (Land Type Survey Staff, 1984; Bezuidenhout,1993).

5.2 B land type

This unit has a plinthic catena but the upland duplex and margalitic soils are rare. A large part of the study area is covered with B land type soils. Plinthic soils cover more than 10% whilst upland duplex and margalitic soils are absent or occupy less than 10% of the area. The following information can serve to distinguish between the Ba, Bb, Bc and Bd land types. Soils of the Ba land type unit are red and or yellow apedal, dystrophic and or mesotrophic predominate over red and or yellow apedal soils that are eutrophic, in which the red soils occupy more than a third of the area. The dominant soil form is Hutton (30% of the Ba land type) with a variety of other soil forms present in the land type. The same rule, with appropriate adaptations applies to Bb (dystrophic and/or mesotrophic, red soils not widespread), Bc (eutrophic, red soils widespread) and Bd (eutrophic, red soils not widespread) (Land Type Survey Staff, 1984). In the Bc land type both Hutton and Mispah soil forms are dominant (21% of the land type) while in the Bb and Bd land type the yellow soils such as Avalon and or Pinedene (23% of the land type) and sometimes Clovelly soil forms are dominant in these land types (Land Type Survey Staff, 1984; Bezuidenhout, 1993).

5.3 F land type

This group forming the F land type is intended to accommodate pedologically young landscapes that are not predominantly rock, alluvial or aeolian and in which the dominant soil forming processes have been rock weathering, the formation of orthic topsoil horizons and generally clay illuviation, typically giving rise to lithocutanic horizons. The soil forms which epitomise these processes are Glenrosa and Mispah. The Fa land type unit refers to land in which lime in the soil is not encountered regularly in any part of the landscape. The dominant soil forms are Glenrose and Mispah (50% of the land type) while Hutton soil form (39% of the land type) is also present. The Fb land type is synonymous with land where lime occurs regularly (in small quantities) in one or more valley bottom soils. The dominant soil forms are Glenrosa (25% of the land type) and Mispah (24% of the land type) with rocks (20% of the land type) also prominent in this land type (Land Type Survey Staff, 1984; Bezuidenhout, 1993).

5.4 I land type

The map units that comprise the I land type refer to miscellaneous land classes with a soil pattern that is difficult to accommodate elsewhere in the land type classes and which at least 60% comprises pedologically youthful, deep (>1000 mm to the underlying rock) unconsolidated deposits. The most common soil forms of this land type are Dundee and Oakleaf. The Ib land type unit indicates land types with exposed rock (exposed country rock, stones or boulders) covering 60 to 80 % of the area. The rocky portions of Ib may be underlain by soil which would have qualified the unit for exclusion in another broad soil pattern if it were not for the surface rockiness (Land Type Survey Staff, 1984).

The land type and soils in the Mooi River Catchment closely reflect the underlying geology of the region and are depicted in Tables 5.1.

Table 5.1: Soil classification of the Mooi River Catchment

Land type	Geology	Soils
Ab	Dolomite and chert of the Chuniespoort Group (Transvaal Sequence), with Pretoria Group quartzite predominant in the north	Red-yellow apedal, freely drained soils devoid of water tables which does not qualify as a plinthic catena, In the Ab land type, the yellow soils occupy less than 10% of the area, whilst dystrophic and or mesotrophic soils occupy a larger area than high base status red-yellow apedal soils. The dominant soil form is Hutton (90% of the land type) and less than 6% of the soils of the A land type are Glenrosa and Mispah soil forms (Land Type Survey Staff, 1984; Bezuidenhout,1993).
Ae	Dolomite and chert of the Chuniespoort Group (Transvaal Sequence)	Red-yellow apedal, freely drained soils devoid of water tables which does not qualify as a plinthic catena, Soils of the Ae land type unit differ from the Ab land type in that it is deeper than 300 mm and no dunes are present. The dominant soil form is Hutton (90% of the land type) and less than 6% of the soils of the A land type are Glenrosa and Mispah soil forms (Land Type Survey Staff, 1984; Bezuidenhout,1993).
Ba	Witwaterrand quartzites, shales and slates, and Ventersdorp Lavas of the Ventersdorp Supergroup and Transvaal Sequence	Soils are predominately red and/or yellow apedal (structurless), dystrophic and or mesotrophic predominate over red and or yellow apedal soils that are eutrophic, in which the red soils occupy more than a third of the area. Land Type Survey Staff (1984) estimate that 2.9% of the Ba land type is unsuitable for agronomy • Upslope: Hutton, Glenrosa and Mispah Forms • Midslope: Hutton, Clovelly, Mispah and Glencoe Forms • Bottomslope/floodplain: Westleigh, Clovelly and Glencoe Forms
Bb	Witwaterrand quartzites, shales and slates, and Ventersdorp Lavas of the Ventersdorp Supergroup and Transvaal Sequence	Dystrophic and/or mesotrophic, red soils not widespread. Dominant soil forms include Hutton and Mispah Forms in the upperslope areas, Glenrosa, Hutton, Glencoe and Mispah Forms in the midslope areas, and Valsrivier, Glencoe, Hutton and Willowbrook Forms in the bottomslope/ flood plain area.
Bc	Witwaterrand quartzites, shales and slates, and Ventersdorp Lavas of the Ventersdorp Supergroup and Transvaal Sequence	Plinthic catena, upland duplex and margalitic soils rare, eutrophic, red soils widespread. Dominant soil forms include Mispah and Hutton Forms in the upperslope areas, Glenrosa Hutton, and Mispah Forms in the midslope areas, and Hutton, Swartland, Rensburg and Valsrivier Forms in the bottomslope/ flood plain area.
Bd	Pretoria Group quartzite and shale with sporadic occurrence of dolerite and diabase	Eutrophic, red soils not widespread Dominant soil forms include the Avalon and/or Pinedene Forms (23% of the land type) and sometimes the Clovelly Form.
Fa	Dolomite and chert of the Chuniespoort Group (Transvaal Sequence)	Lime in the soil is not encountered regularly in any part of the landscape.Land Type Survey Staff (1984) estimate that 35% of the Fa land type is unsuitable for agronomy. More than 50% of the main soil types are relatively shallow (between 50 and 150 mm) and rocky (dolomite and chert). Dominant soil forms include Mispah, Glenrosa and shallow Hutton
Fb	Shale, slate and quartzite of the Pretoria Group with inter-layered diabase sills and Hekpoort lava. Chert, dolomite and Black Reef Quartzite are present in some places	Land Type Survey Staff (1984) estimate that between 5% to 10% of the Fb land type is unsuitable for agronomy. Yet very little of this land type has been ploughed due in part to the fact that the mining companies own much of the Fb land type area, however, the main reason for not ploughing is that the dominant soil types are relatively shallow (between 100 and 350 mm) and rocky. The dominant soil forms include the Glenrosa, Mispah and shallow Hutton Forms.

Ib	Quartzite, shale, slate and conglomerate of the Witwatersrand Supergroup with sporadic occurrence of diabase sills	The Ib land type unit indicates land types with exposed rock (exposed country rock, stones or boulders) covering 60 to 80 % of the area. The rocky portions of the Ib land type may be underlain by soil which would have qualified the unit for exclusion in another broad soil pattern if it were not for the surface rockiness (Land Type Survey Staff, 1984). The most common soil forms of this land type are Dundee and Oakleaf Forms.

6 Natural vegetation

The natural vegetation of the Mooi River Catchment has dramatically been altered due to cultivation and mining in the area. According to Acocks (1988) and Rutherford and Westfall (1994) the natural vegetation of the Mooi River Catchment has a high biodiversity and the areas of natural vegetation that remain in the catchment area are isolated and the conservation status low. Acocks (1988) defines the vegetation as Cymbopogon-Themeda veld, a mixed to sour grassveld where *Setaria flabella* and *Themeda trianda* are the dominant species, and the western variation of Bakkenveld, a false grassland where the presence of important quantities of *Cymbopogon plurinodis*, and the general absence of *Tristachya hispida* distinguish it from the Central and Eastern variations.

This is in contrast to the new natural vegetation classification for South Africa which is based on biomes. The result being a new baseline map that can be used for more than agricultural planning and potential, on which Acocks classification is based. The new classification arose as a result of changes in the approach to and concepts in vegetation classification over that past three decades as well as the fact that considerable new information has been collected. The need for a new up-to date map, therefore, gave rise to the new classification essential to planning, development and conservation as well as being a vital tool in education. Based on the new classification, the Mooi River Catchment is divided into grassland of the Rocky Highveld Grassland and Dry Sandy Highveld Grassland.

The term biome can be defined as a unit which "represents large, natural, reasonably homogenous areas of the Earth's biotic and abiotic surface mantle (Rutherford and Westfall, 1996:1)." The importance of which include the fact that the diagnostic elements form the lowest common denominator needed for extensive comparisons; it indicates the usual general limits for extrapolation of many ecological functional patterns and solutions to environmental problems within each biome; it provides an initial framework for national and environmental planning and organisation of scientific research; and it enable bias contained in certain detailed work to be viewed in a new perspective (Rutherford and Westfall, 1996).

The Grassland Biome is located mainly on the high central flat and rolling plateau of South Africa, the inland areas of KwaZulu Natal (including the escarpment) and the Eastern Cape. Altitude varies from approximately 300m above mean sea level to 2850m above mean sea level in the Drakensberg. The Grassland Biome is limited to summer rainfall areas between 400 mm and 2000 mm. Frosts (±30-180 days), thunder and lightening (±70 days) and hail (> 5 hail storms/year) are all common associated with the Grassland Biome (Rutherford and Westfall, 1994). As a consequence, geophytes are often abundant. The grassland biome is dominated by a single layer of grasses, whereby the amount of canopy cover is dependant on rainfall and the degree of grazing. Trees are mainly absent, except in a few localised habitats. Frosts, fire and grazing maintain the grass dominance and prevent the establishment of trees.

Two categories of grass plants exist, namely, 'sweet' and 'sour' grasses. 'Sweet' grasses usually have a lower fibre content, maintain their nutrients in the leaves in winter and are, therefore, palatable to stock. 'Sour' grasses, on the other hand, have a higher fibre content and tend to withdraw their nutrients from the leaves during winter so that they are unpalatable to stock. The division between the two grass categories is dependant on rainfall. At higher rainfall and on more acidic soils, the sour grasses tend to prevail, with 625 mm per year taken as the level at which the unpalatable grasses predominate. Although grass plants of the Grassland Biome are tolerant of grazing and fire, overgrazing of the grass species tends to increase the proportion of pioneer, creeping and annual grasses. Management in the transitional zones between sweet and sour grass dominance is, therefore, required to maintain the abundance of sweet grasses. Agricultural threats to the grassland biome include maize, sorghum, wheat and sunflower crops, while sprawling urbanisation in the Witwatersrand, poses an additional threat.

6.1 Rocky highveld grassland

The vegetation of the rocky highveld grassland is defined as a transitional type of vegetation found mainly between the typical grasslands of the high inland plateau and the bushveld of the lower inland plateau (Bredenkamp and van Rooyen, 1996). Stretching from Lichtenburg in the North West Province to Middleburg in Mapumalanga and covering an area of approximately 240 633 km^2, the rocky highveld grassland also including the southern slopes of the Magaliesberg, the ridges of the Witwatersrand and the dolomitic plains of Gauteng and the North West Province and is located between an altitude of 1500 to 1600 m above mean sea level. The habitat is rocky mountains, hills, ridges and plains of quartzite, conglomerate, shale, dolomite and sometime andesitic lava. Climatic characteristics include summer rainfall (650 to 750 mm per year) and temperatures which vary between -12°C and 39°C, with an average of 16°C.

Acocks (1988) describes the Bakkenveld as a fire maintained false grassland, that would develop into savanna if fire was excluded. Frost during the winter months play the most important role in the distribution of the woody elements in this transitional zone. Grassland vegetation is restricted to exposed sites in the irregular, undulating, high altitude landscape, especially on the crests of rocky hills and ridges. Maize production is limited due to the shallow, rocky soils. Grazing by cattle is often found in this vegetation type, but the dominance of sour grass species often results in a low nutrient status of the grass during winter. In the Gauteng area the vegetation is highly threatened by urbanisation, industrialisation and mining and to a lesser degree agriculture. Of the total area, ± 65% has already been transformed. The rocky highveld grassland is poorly conserved (1.38%) in the Suikerbosrand, Rustenburg, Abe Bailey and Boskop Dam Nature Reserves, and several smaller reserves managed by local authorities within the metropolitan area.

6.2 Dry Sandy Highveld Grassland

The grassveld of the dry sandy highveld is found primary on the plains in the dry western parts of the Free State and south eastern parts of the North West Province. The landscape is flat to undulating (1370 to 1460 m), while the summer rainfall is erratic (average: 450 mm per year). Temperatures vary between -11°C and 41°C with an average of 18°C. The soils are deep, red to yellow, apedal aeolian sand which often cover and are associated with limestone. The erratic summer rainfall makes this a high risk area for agronomy. Even with the erratic rainfall and high risk associated with agronomy, crops such as maize, have replaced the grazing for which the area is better suited.

The conservation status of the vegetation type is very poor (0.28%) . Although an excellent cattle and sheep farming area, many areas have been ploughed for the cultivation of maize (± 65% transformed). Today the natural vegetation is only represented by small remnants which are often degraded as a result of overgrazing.

Detailed syntaxonomy and synecology of the vegetation of the Mooi River Catchment and Far West Rand has been extensively studied by Bezuidenhout (1988); Bezuidenhout and Bredenkamp (1990); Bezuidenhout and Bredenkamp (1991a); Bezuidenhout and Bredenkamp(1991b); Bezuidenhout and Bredenkamp (1991c); Bezuidenhout and Bredenkamp (1991d); Bezuidenhout(1993); Bezuidenhout *et al.*, (1993a); Bezuidenhout *et al.*,(1993b); Bezuidenhout *et al.*, (1993c); Bezuidenhout *et al.*, (1993d); Bezuidenhout *et al.*, (1994); Bredenkamp *et al.*, (1989); Bredenkamp *et al.*, (1993) using Land Type, as defined by the Land Type Survey Staff (1984), as the base unit for classification of the various vegetation habitats. A summary of the results of these studies is outlined in Table 6.1.

Table 6.1: Vegetation of the Mooi River Catchment (modified after Bezuidenhout (1988); Bezuidenhout and Bredenkamp (1990); Bezuidenhout and Bredenkamp (1991a); Bezuidenhout and Bredenkamp (1991b); Bezuidenhout and Bredenkamp (1991c); Bezuidenhout and Bredenkamp (1991d); Bezuidenhout (1993); Bezuidenhout, Bredenkamp and Theron (1993a); Bezuidenhout, Bredenkamp and Theron (1993b); Bezuidenhout, Bredenkamp and Theron (1993c); Bezuidenhout, Bredenkamp and Theron (1993d); Bezuidenhout, Bredenkamp and Theron (1994); Bredenkamp, Joubert, and Bezuidenhout, (1989) and Bredenkamp, Bezuidenhout, Joubert and Naude (1993)).

Land type	Habitat	Habitat Description	Vegetation
Ab	Grassland		
	• Crest	• Relatively high altitude, rocky grassland, <20% clay, depth < 300mm well drained soils predominantly of the Ms and Gs forms	• Elionurus muticus - Themeda trianda - Trachypogon spicatus - Lightfootia denticulata varient
	• Scarp	• Relatively high altitude rock free grassland, <20% clay, depth < 300mm well drained soils predominantly of the Ms and Gs forms	• Elionurus muticus - Themeda trianda - Trachypogon spicatus - Sphenostylis angustifolia varient
	• Midslope	• Relatively high altitude, rock free, degraded grassland, <20% clay, depth > 300mm well drained soils predominantly of the Ms and Gs forms	• Elionurus muticus - Themeda trianda - Trachypogon spicatus - Ziziphus zeyheriana varient
	• Bottomland flats	• Relatively high altitude grassland, 20 - 25% clay, well drained soils on the flood plain soils predominantly of the Hu form	• Elionurus muticus - Themeda trianda - Aristida stipitata
	• Drainage line	• Relatively low altitude grassland, poorly drained soils with > 25% clay, soils predominantly of the Hu form	• Eragrostis plana -Setaria sphacelata
Ae	Woodland:		
	• Bottomland	• Low altitude woodland, relatively dry habitat, well drained soils Hu (30%), Ms (19%) and Cv (11%)	• Tarchonantho camphorati - Acacietum karoo
	• Footslope	• High altitude woodland, relatively dry habitat, well drained soils Av (30%), We (20%) and Ge (10%)	• Stipagrosto uniplumis - Acacietum eriolobae
Ba	Woodland:		
	• Bottomland flats	• Low altitude poorly drained woodland, (3-8% slope), 20-30% clay (B horizon), depth 300-1050mm Gc (30%), Lo (23%) and Fw (22%)	• Protasparago suaveolentis - Acacietum karroo
	• Footslope	• Low altitude poorly drained woodland, (2-6% slope), 18-30% clay (B horizon), depth 900-1100mm Hu (47%), Ms (11%) and Av (10%)	• Eragrostido curvulae - Acacietum karroo
	• Midslope	• High altitude well drained woodland, (0-2% slope), 18-30% clay (B horizon), depth 900-1100mm Hu (37%), rock (27%) and Ms (26%)	• Rhoo lanceae - Acacietum caffrae
	Shrubland:		
	• Scarp	• High altitude well drained shrubland, rocky outcrops, >100% slope, 3-10% clay (A horizon), depth 100-200mm rock (90%) and Ms (10%)	• Zanthoxylo capensis - Vanguerietum infaustae

	Crest	High altitude well drained shrubland, rocky outcrops, 0-5% slope, 3-10% clay (A horizon), depth 100-200mm Ms (23%), Gc (20%) and Hu (19%)	Pavetto zeyheri - Vanguerietum infaustae
	Grassland:		
	Scarp	High altitude very rocky dry habitat, slope >100%, 6-20% clay (A horizon), depth 100-200mm Ms (35%), Gs (22%) and Hu (14%)	Alloteropsido semialatae - Pogonarthrietum squarrosae
	Midslope (very rocky)	High altitude very rocky dry habitat, slope 2-3%, 6-20% clay (A horizon), depth 100-200mm rock (60%), Ms (30%) and Gs (10%)	Aristido stipitatae - Pogonarthrietum squarrosae
	Midslope (less rocky)	High altitude less rocky dry habitat, slope 2-6%, 10-20% clay (A horizon), depth 900-1100mm Hu (47%), Ms (11%) and Av (10%)	Elionurio mutici - Cymbopogonetum plurinodis eragrostidetosum racemosae
	Midslope (no rocks)	High altitude, no rock or stone, dry habitat, slope 2-3%, 10-20% clay (A horizon), depth 900-1100mm Hu (47%), Ms (11%) and Av (10%)	Elionurio mutici - Cymbopogonetum plurinodis aristidetosum canescentis
	Bottom flats	Low altitude, rock free, wetter habitat, 2-3% slope, 30-40% clay (B horizon), depth 200-550mm Va (33%), We (20%0 and Gc (10%)	Themeda trianda - Cymbopogon plurinodis Grassland
	Drainage line (wet)	Low altitude, rock free, wetter habitat, 0-1% slope, 35-50% clay (B horizon), depth 600-900mm Rg, Wo and Ar > 90%	Falckio oblongae - Eragrostidetum planae verbenetosum bonariensis
	Drainage line (dry)	Low altitude, rock free, drier habitat, 0-1% slope, 35-50% clay (B horizon), depth 600-900mm Rg, Wo and Ar > 90%	Falckio oblongae - Eragrostidetum planae cirsetosum vulgaris
Bb and Bc	Woodland:		
	Footslope	High altitude woodland, relatively dry habitat (> 3% slope), rocks or stones (> 10%), soils Hu (45%), Ms/Gs (40%) and Litho (7%)	Sporobolo africani-Acacietum karroo ziziphetosum mucronatae
	Midslope	High altitude woodland, relatively dry habitat (0-3% slope), rocks or stones (< 10%), soils Ms/Gs (36%), Hu (33%), and Litho (3%)	Sporobolo africani-Acacietum karroo nidorelletosum resedifoliae
	Crest	High altitude woodland, relatively wetter habitat, very rocky, soils litho (70%) and Ms/Gs (30%)	Vanguerio infaustae-Acacietum caffrae
	Bottomland flats	Low altitude woodland, relatively wetter habitat, no rocks or stones, soils Hu (31%), Sw (26%) and We (22%)	Elionurus muticus-Acacia karroo community
	Grassland:		
	Plateau	High altitude grasslands, relatively dry habitat, mostly rocks or stones (>35%), soils Ms/Gs (50%), litho (45%) and Hu (5%)	Trachypogono spicati-Triraphietum andropogonoidis helicrysetosum miconiifolii
	Crest	High altitude grasslands, relatively dry habitat, mostly rocks or stones (10-35%), soils Ms/Gs (41%), Hu (30%) and litho (25%)	Trachypogono spicati-Triraphietum andropogonoidis aristidetosum diffusae
	Midslope	High altitude grasslands, relatively dry habitat, rocks or stones (<10%), soils Ms/Gs (36-40%), Hu (33-45%) and litho (3-7%)	Sporobolo discospori-Heteropogonetum contorti

	• Midslope/footslope	• High altitude grasslands, relatively dry habitat, no rocks or stones, soils Ms/Gs (31%), Va (17%) and Hu (13%)	• Themedo triandrae-Heteropogonetum contorti
	• Footslope/drainage line	• Low altitude grassland, relatively wetter habitat, no rocks or stones, soils Rg (52%) and Va (36%)	• Aristida bipartita Varient
	• Footslope	• Low altitude grassland, relatively drier habitat, no rocks or stones, soils Rg (52%) and Va (36%)	• Themeda triandra Varient
Bd	Woodland:		
	• Bottomland	• Low altitude woodland, relatively dry habitat, soils Va/Sw (71%), Ms (11%) and Ss (7%)	• Rhoo pyroidis - Acacietum karroo protasparagetosum africani
	• Bottomland	• Low altitude woodland, relatively dry habitat, soils Va/Ss (70%), We (10%) and Ms/Gs (10%)	• Rhoo pyroidis - Acacietum karroo nidorelletosum resedifoliae
	• Footslope	• High altitude woodland, relatively dry habitat, well drained soils Av (30%), We (20%) and Ge (10%)	• Stipagrosto uniplumis - Acacietum eriolobae
	Grassland:		
	• Midslope	• High altitude grassland, relatively dry habitat, well drained soils Hu (25%), Av (15%) and Ms (12%)	• Trirapho andropogonoidis - Elionuretum mutici
	• Midslope	• High altitude grassland, relatively dry habitat, well drained soils Cv/Gc (31%), Av (17%) and Gs (15%)	• Sporobolo fimbriati - Elionuretum mutici
	• Footslope	• Low altitude grassland, relatively dry habitat, well drained soils Av/Pn (32%), Cv (21%) and Hu (11%)	• Themeda trianda - Elionurus muticus Grassland
	• Floodplain	• Low altitude grassland, relatively wet habitat, poorly drained soils Rg/Ka (56%) and Ss/Va (40%)	• Circio vulgaris - Eragrostidetum planae
Fa	Woodland:		
	• Sinkholes	• Low altitude woodland confined to sinkholes, clay content <10%, soil depth 300->1200mm Hu (50%), Ms/Gs (33%) and rock (17%)	• Rhoo lanceae- Acacietum eroiobae
	• Footslopes	• Low altitude woodland, clay content >20%, soil depth 250-1200mm Hu (50%), Ms/Gs (25%) and rock (25%)	• Zizipho mucronatae- Acacietum karroo
	Shrubland:		
	• Midslope	• Low altitude shrubland confined to ruins and diamond diggings, soil depth >1200-2500mm Hu (47%), Ms/Gs (46%) and rock (7%)	• Digitaria eriantha- Rhus pyroides Shrubveld
	Grassland:		
	• Plateau	• High altitude grassland on very rocky chert outcrops and ridges, soil depth 50-150mm rock (67%) and Ms/Gs (33%)	• Loudetio simplicis- Diheteropogonetum amplectentis

	• Plateau	• High altitude grassland on very rocky chert outcrops and ridges, soil depth 300-900mm Ms/Gs (72%), rock (16%) and Hu (12%)	• Alloteropsido semialatae- Tristachyetum leucothricis
	• Midslope	• High altitude grassland on less rocky chert outcrops and ridges, soil depth 100-150mm Ms/Gs (88%), rock (8%) and Hu (4%)	• Cymbopogon excavatus- Diheteropogon amplectens Grassland
	• Midslope	• High altitude grassland confined to the dolomite, soil depth 250-1200 mm Hu (47%), Ms/Gs (46%) and rock (7%)	• Cymbopogono plurinodis- Eragrostidetum gummifluae aristidetosum canescentis
	• Floodplain	• Low altitude grassland, rocks or stones >5%, soil depth 250-1200 mm Hu (50%), Ms/Gs (33%) and rock (17%)	• Cymbopogono plurinodis- Eragrostidetum gummifluae eragrostidetosum superbae
	• Drainage line	• Low altitude grassland with no rocks or stones, soil depth 300-800 mm We/Va (40%), Hu (40%) and Ms/Gs (14%)	• Paspalo dilatati- Hyparrhenietum hirtae
Fb	Woodland:		
	• Footslope	• Low altitude woodland (0-3% slope), sometimes with rocks and stones, soils Hu (48%) and Gs (12%)	• Acacietum karroo-caffrae rhoetosum pyroidis
	• Footslope/ midslope	• Low altitude woodland (3-6% slope), sometimes with rocks and stones, soils Gs/Ms (35%) and Hu (32%)	• Acacietum karroo-caffrae barlerietosum macrostegiae
	• Crest	• High altitude woodland, rocky outcrop, soils rock (40%) and Ms/Gs (33%)	• Rhoo rigidae-Acacietum caffrae
	• Scarp	• High altitude woodland, sheet outcrop, soils rock (70%) and Ms (20%)	• Dombeyo rotundifoliae-Acacietum caffrae
	• Midslope	• High altitude woodland, boulders, soils Gs/Ms (29%) and Hu (23%)	• Proteo caffrae-Acacietum caffrae
	Grassland:		
	• Plateau	• High altitude grassland, relatively dry habitat, mostly rocks or stones, soils Ms (33%) and Gs (23%)	• Monocymbio ceresiiformis-Schizachyrietum sanguinei
	• Midslope	• High altitude grassland, relatively dry habitat, mostly rocks or stones, soils Gs/Ms (29%) and Hu (23%)	• Uryletro agropyroidis-Schizachyrietum sanguinei
	• Drainage line	• High altitude grassland, relatively wet habitat, mostly boulders, soils Ar/Rg (52%) and Ms (16%)	• Hyparrhenio hirtae-Eragrostidetum planae
Ib	Woodland:		
	• footslope	• High altitude woodland, sporadic quartzite rocks and boulders, moderately deep Hutton soil forms	• Arisitida canescens - Acacia karoo
	• plain	• High altitude woodland, sporadic quartzite rocks and boulders, moderately deep Hutton soil forms	• Arisitida canescens - Acacia karoo

7 Socio-economic structure and land use

The socio-economic structure of the Mooi River catchment is closely aligned to the mining that takes place in the region.

Table 7.1: Provincial statistics for Gauteng and North West Province (Stats SA, 1999)

	Gauteng	Northwest Province
Area	1.4%	9.5%
population percentage	18.1%	8.3%
Density (people/km^2) (national average 33.8)	374.7	28.8
Total population	7 348 423	3 354 825
African/Blacks	70% (5 147 444)	91.2% (3 058 686)
Coloured	3.8% (278 692)	1.4% (46 652)
Indian/Asians	2.2% (161 289)	0.3% (10 097)
Whites	23.2% (1 702 343)	6.6 % (222 755)
Unspecified/Other	0.8% (58 654)	0.5% (16 635)
Urban	7 130 277	1 171 734
Non Urban	218 146	2 183 091
Urbanisation	97%	34.9%
Afrikaans speaking	16.7%	7.5%
English speaking	13.0%	1.0%
IsiXhosa speaking	7.5%	5.4%
IsiZulu speaking	21.5%	2.5%
Setswana speaking	7.9%	67.2%
Other languages	IsiNdebele (1.6%), Sepedi (9.5%), Sesotho (13.1%), Si Swati (1.3%), TshiVenda (1.4%), Xitsonga (5.3%), Other (1.3%)	IsiNdebele (1.3%), Sepedi (4.0%), Sesotho (5.1%), Si Swati (0.5%), TshiVenda (0.4%), Xitsonga (4.7%), Other (0.5%)
Life expectancy (national average 62.8 years)	66 years	59.7
Adult literacy rate (national average 82.2)	92.9%	69.5
Per capita income (national average R 8 704)	R19 261	R 5817
Mining industry	5.1% (159 mines, 44 gold which employ more than 190 000 people)	40.6
Tertiary sector	61.6%	
Manufacture	27.1	
GDP	37.7	
Inflation rate (national average 8.7%)	8.6%	8.7%

The land use of the Mooi River Catchment is characterised by urbanisation, both formal and informal, urban and rural; mining which includes both the gold mines as well as the diamondiferous gravel digging in the area around the river courses; industry; agriculture (subsistence and commercial farming); and nature reserves. Each of the above mentioned categories will be discussed in greater detail below.

7.1 Urbanisation

Urbanisation in the Mooi River Catchment is concentrated into three separate node areas of development namely, the Krugersdorp/Randfontein/Westonaria node in the north-east of the catchment, the Carletonville/Welverdiend/Fochville node in the centre of the catchment and the Potchefstroom node in the south-west. The development of each of the above-mentioned nodes is derived from different stages in the history of South Africa. The town of Potchefstroom was founded by Andries Hendrik Potgieter in 1838 and was the first white town to be established north of the Vaal River. In 1857, Potchefstroom became the capital of the Republic of South Africa, and Marthinus Wessel Pretorius the first president. In 1881, the first shot of the Transvaal War of Independence was fired at Potchefstroom and during the South African gold rush it earned worldwide fame as the gateway to a new El Dorado.

The histories of the Krugersdorp/ Randfontein/ Westonaria and the Carletonville/ Welverdiend/ Fochville nodes of development are closely linked to the extensive gold reserves discovered in the Witwatersrand area. Krugersdorp and Randfontein arose as a result of gold mining at the turn of the centuary and Carletonville, Westonarea, Welverdiend and Fochville developed later as gold bearing ore in the deeper underlying geology was found and mining techniques improved such that ore can be mined at depths below surface.

7.2 Mining and industry

As mentioned above in the development of urbanised areas in the Mooi River, gold mining forms a large component of the landuse in the Wonderfontein Spruit and Loop Spruit, particularly the tailings dams and rock dumps associated with the waste products of mining. Diamondiferous gravel diggings are common along the Mooi River between the Klerkskraal Dam and the confluence with the Vaal River. Diamondiferous gravel diggings, as with sand winnowing, are difficult to quantify as the operations are so mobile and move rapidly. Industries in the Mooi River Catchment are limited to the urbanised nodes of development and tend to concentrate as support businesses to the mining industry.

7.3 Agriculture

Agriculture forms a large part of the landuse in the Mooi River Catchment and includes both crops and livestock farming. Irrigation farming form the nucleus of farming in the area, although dry land cropping was intensive before 1960. Irrigated crops in the Mooi River Catchment includes crops of asparagus, kikuju grass, cabbage, lettuce, peas, potatoes, pumpkin, lucerne, fodder, rye grass, oats, maize, carrots, sweet corn, wheat and fruit trees. Other crops not mentioned include spinach, beetroot, sorghum, beans, clover and tomatoes. Most irrigation consists of sprinkle and flood irrigation adjacent or near the river course. Livestock agriculture, although not as prevalent, includes cattle, pigs, horses, sheep, milk cows, ostriches and chickens.

7.4 Nature reserves

A small, however, important land use in the Mooi River catchment comprises nature reserves and recreational areas. Nature reserves and recreational areas in the Mooi River catchment include the Boskop Nature Reserve at Boskop Dam, the Mooi River Trail, Trim Park, Lakeside (Potchefstroom) Dam and the Fanie du Toit Sports Centre in Potchefstroom, the OPM Prozesky Bird Sanctuary south of Potchefstroom, the Dam Recreational Facility, Donaldson Dam east of Westonarea and the Abe Bailey Nature Reserve just outside Carletonville. These reserves are important conservation areas protecting wetland, riverine and lake habitats, fauna and flora. In addition, numerous recreational activities are practised in, on and alongside the natural reserves. Such activities include swimming, angling, canoeing, power boating, sailing and hiking.

APPENDIX B

wonder.wdm as at Mon Apr 23 14:30:54 2001

Ds	Station Id	Type	Agency	Start	End	Units	Name
1	Pothcefstroom	EVAP		1950/1/1	1998/12/31	Unknown	Potchefstroom generated evaporation
2	Krugersdorp	EVAP		1950/1/1	1998/12/31	Unknown	Krugersdorp generated evaporation
3	Welverdiend	EVAP		1950/1/1	1998/12/31	Unknown	Welverdiend generated evaporation
10	0437104	PRCP		1950/1/1	1997/11/30	mm	
11	0474255	PRCP		1950/1/1	1997/11/30	mm	
12	0474502	PRCP		1950/1/1	1997/11/30	mm	
13	0474899	PRCP		1950/1/1	1997/11/30	mm	
14	0475370	PRCP		1950/1/1	1997/11/30	mm	
15	0475456	PRCP		1950/1/1	1997/11/30	mm	
16	0475611	PRCP		1950/1/1	1997/11/30	mm	
17	0474680	PRCP		1954/9/1	1997/11/30	mm	
18	0474684	PRCP		1950/1/1	1997/11/30	mm	
19	0474742	PRCP		1950/1/1	1997/11/30	mm	
20	0475338	PRCP		1950/1/1	1997/11/30	mm	
101	C2H001	FLOW		1904/8/1	1996/6/30	m3/s	MOOI RIVER, WITRAND
102	C2H004	FLOW		0	0	Unknown	UITVLUGT
103	C2H006	FLOW		1906/7/1	1966/7/31	m3/s	MOOI RIVER, KLERKSKRAAL
104	C2H008	FLOW		1952/9/1	1996/9/30	m3/s	VAAL RIVER, WOODLANDS LINDEQUESDRIF
105	C2H011	FLOW		1947/1/1	1996/4/30	m3/s	GERHARDMINNEBRON-EYE, GERHARDMINNEBRON
106	C2H013	FLOW		1912/2/1	1997/2/28	m3/s	TURFFONTEIN UPPER EYE, TURFFONTEIN
107	C2H018	FLOW		1938/10/1	1996/5/31	m3/s	VAAL RIVER DE VAAL, SCHOEMANSDRIFT
108	C2H023	FLOW		1957/10/1	1994/11/30	m3/s	WONDERFONTEIN SPRUIT, LUIPAARDSVLEI
109	C2H024	FLOW		1957/10/1	1996/4/30	m3/s	WONDERFONTEIN SPRUIT, GEMSBOKFONTEIN
110	C2H025	FLOW		1959/10/1	1996/5/31	m3/s	WONDERFONTEIN- SPRUIT 7, GEMSBOKFONTEIN
111	C2H026	FLOW		1995/8/1	1996/6/30	m3/s	MIDDELVLEI SPRUIT, MIDDELVLEI
112	C2H027	FLOW		1957/10/1	1992/9/30	m3/s	KOCKSOORD SPRUIT, MIDDELVLEI
113	C2H028	FLOW		1957/10/1	1993/3/31	m3/s	RIETFONTEIN SPRUIT, RIETFONTEIN
114	C2H030	FLOW		1957/12/1	1996/9/30	m3/s	LEFT PRINCIPAL CANAL, EYE OF WONDERFONTEIN
115	C2H031	FLOW		1958/3/1	1966/4/30	m3/s	MOOIRIVIERLOOP, WONDERFONTEIN
116	C2H032	FLOW		1958/4/1	1987/5/31	m3/s	MOOIRIVIERLOOP, WONDERFONTEIN
117	C2H035	FLOW		1959/10/1	1970/11/30	m3/s	MOOIRIVIERLOOP, WELVERDIEND
118	C2H037	FLOW		1960/12/1	1963/10/31	m3/s	DU TOIT SPRUIT, DU TOITS SPRUIT
119	C2H044	FLOW		1957/12/1	1996/6/30	m3/s	OBERHOLZER CANAL SOUTH, WONDERFONTEIN
120	C2H045	FLOW		1980/9/1	1992/11/30	m3/s	WEST DRIEFONTEIN CANAL SOUTH, VLAKPLAATS
121	C2H051	FLOW		1966/4/1	1994/10/31	m3/s	KRAALKOP-EYE, KRAALKOP
122	C2H054	FLOW		1966/5/1	1971/12/31	m3/s	CANAL FROM VENTERS- POS SILT DAM 1, VENTERSPOS

123	C2H055	FLOW	1966/5/1	1979/7/31	m3/s	CANAL FROM VENTERS- POS SILT DAM 2, VENTERSPOS
124	C2H056	FLOW	1966/5/1	1970/2/28	m3/s	WONDERFONTEINSPRUIT, EYE OF WONDERFONTEIN
125	C2H057	FLOW	1967/1/1	1996/4/30	m3/s	WEST DRIEFONTEIN CANAL, WONDERFONTEIN
126	C2H058	FLOW	1968/3/1	1971/1/31	m3/s	LOWER BANK CANAL, WONDERFONTEIN
127	C2H059	FLOW	1968/10/1	1979/7/31	m3/s	GEMSBOKFONTEIN CANAL, VENTERSPOS
128	C2H060	FLOW	1969/8/1	1992/12/31	m3/s	DOORNFONTEIN CANAL, BLAAUWBANK
129	C2H063	FLOW	1974/10/1	1996/6/30	m3/s	WEST DRIEFONTEIN CANAL, ROOIPOORT
130	C2H068	FLOW	1973/11/1	1978/2/28	m3/s	WEST DRIEFONTEIN BY-PASS CANAL, WONDERFONTEIN
131	C2H069	FLOW	1971/5/1	1997/3/31	m3/s	MOOIRIVIERLOOP, BLAAUWBANK
132	C2H085	FLOW	1986/9/1	1996/6/30	m3/s	MOOI RIVER, HOOGEKRAAL KROMDRAAI
133	C2H092	FLOW	1938/10/1	1995/9/30	m3/s	CANAL FROM GERHARDMINNEBRON-EYE, GERHARDMINNEBRO
134	C2H103	FLOW	1957/10/1	1960/11/30	m3/s	LEFT CANAL FROM RIETFONTEIN SPRUIT, RIETFONTEIN
135	C2H105	FLOW	1970/7/1	1993/8/31	m3/s	OBERHOLZER CANAL- SOUTH (LITTLE), WONDERFONTEIN
136	C2H107	FLOW	1973/11/1	1996/7/31	m3/s	CANAL FROM WEST DRIEFONTEIN, WONDERFONTEIN
137	C2H110	FLOW	1958/11/1	1994/12/31	m3/s	LEFT PRINCIPAL CANAL FROM BOSKOP DAM, NAAUWPOORT
138	C2H111	FLOW	1968/5/1	1994/9/30	m3/s	LEFT CANAL FROM PRINCIPAL CANAL, NAAUWPOORT BOSK
139	C2H112	FLOW	1968/5/1	1994/9/30	m3/s	RIGHT CANAL FROM PRINCIPAL CANAL, NAAUWPOORT BOS
140	C2H114	FLOW	1968/6/1	1993/6/30	m3/s	LEFT CANAL FROM DAM, POTCHEFSTROOM
141	C2H115	FLOW	1968/6/1	1993/8/31	m3/s	CANAL BACK TO MOOI RIVER, POTCHEFSTROOM
142	C2H116	FLOW	1971/12/1	1996/2/28	m3/s	LEFT CANAL FROM DAM, KLIPDRIFT KLIPDRIFT DAM
143	C2H117	FLOW	1971/12/1	1996/2/28	m3/s	RIGHT CANAL FROM DAM, KLIPDRIFT KLIPDRIFT DAM
144	C2H151	FLOW	1997/8/1	1997/9/30	Unknown	OBERHOLZER CANAL SOUTH AT WONDERFONTEINSPRUIT
801	C2H023	HYDR	1951/1/1	1991/1/31	Unknown	C2H023 Simulated flow
802	PIPELINE INFLOW	HYDR	1951/1/1	1991/1/31	Unknown	C2H024 Simulated flow
803	C2H024	HYDR	1955/1/1	1991/1/31	Unknown	1m Pipeline inflow
804	C2H027	HYDR	1955/1/1	1991/1/31	Unknown	C2H027 Simulated flow
805	C2H026	HYDR	1955/1/1	1991/1/31	Unknown	C2H026 Simulated flow
806	C2H028	HYDR	1955/1/1	1991/1/31	Unknown	C2H028 Simulated flow
807	C2H056	HYDR	1955/1/1	1991/1/31	Unknown	C2H056 Simulated flow
808	C2h032	HYDR	1955/1/1	1991/1/31	Unknown	C2H032 Simulated flow
809	C2H069	HYDR	1955/1/1	1991/1/31	Unknown	C2H069 Simulated flow
810	CANAL 1	HYDR	1955/1/1	1991/1/31	Unknown	West Driefontein canal outflow
811	CANAL 2	HYDR	1955/1/1	1991/1/31	Unknown	Clean water canal outflow
812	CANAL 3	HYDR	1955/1/1	1991/1/31	Unknown	Doornfontein/Blijvooruitzicht canal outflow

APPENDIX C

```
RUN

GLOBAL
*** Pg. 290-291
 HSPF Demonstration for Wonderfonteinspruit
 START     1976/01/01      END    1991/01/31
 RUN INTERP OUTPUT LEVEL    4
 RESUME    0 RUN    1 TSSFL    0 WDMSFL    0 UNITS    2
END GLOBAL

FILES
*** Pg. 292-294
<FILE>  <UN#>***<----FILE NAME------------------------------------------->
WDM        21   wonder.wdm
MESSU       22   wonder.ech
          61   wonder.p61
          62   wonder.p62
          63   wonder.p63
          64   wonder.p64
END FILES

OPN SEQUENCE
*** Pg. 295-299
  INGRP             INDELT 24:00

***   Land use 1 = Non-Cultivated
***   Land use 2 = Cultivated
***   Land use 3 = Urban
***   Land use 4 = Slimes

    PERLND     11
    PERLND     12
    PERLND     13
    PERLND     14
    PERLND     21
    PERLND     22
    PERLND     23
    PERLND     24
***  PERLND     31
    PERLND     32
***  PERLND     33
    PERLND     41
    PERLND     42
    PERLND     43
    PERLND     51
    PERLND     52
    PERLND     53
    PERLND     61
    PERLND     62
    PERLND     63
    PERLND     64
    PERLND     71
    PERLND     72
    PERLND     73
    PERLND     74
    PERLND     81
    PERLND     82
    PERLND     83
    PERLND     84
    PERLND     91
    PERLND     92
    PERLND     93
    PERLND     94
    PERLND    101
    PERLND    102
    PERLND    103
    PERLND    104

    Generate point flows ***
    GENER      10
    GENER      20
```

GENER 30
GENER 40
GENER 50
GENER 60
GENER 70
GENER 80
GENER 90
GENER 100
GENER 110
GENER 120
GENER 130
GENER 140
GENER 150
GENER 160
GENER 170
GENER 180
GENER 190
GENER 200

Generate point flow concentrations ***
GENER 310
GENER 320
GENER 330
GENER 340
GENER 350
GENER 360
GENER 370
GENER 380
GENER 390
GENER 400
GENER 410
GENER 420
GENER 430
GENER 440
GENER 450
GENER 460
GENER 470
GENER 480
GENER 490
GENER 500

Generate point flow loads in kg/day ***
GENER 510
GENER 520
GENER 530
GENER 540
GENER 550
GENER 560
GENER 570
GENER 580
GENER 590
GENER 600
GENER 610
GENER 620
GENER 630
GENER 640
GENER 650
GENER 660
GENER 670
GENER 680
GENER 690
GENER 700

*** Reaches in Subcatch 1
RCHRES 11
RCHRES 12
RCHRES 13
*** Reaches in Subcatch 2
RCHRES 21
RCHRES 22
*** Reaches in Subcatch 3
RCHRES 31
*** Reaches in Subcatch 4
RCHRES 41
*** Reaches in Subcatch 5

```
    RCHRES     51
***  Reaches in Subcatch 6
    RCHRES     61
***  Reaches in Subcatch 7
    RCHRES     71
***  1 m pipeline
    RCHRES    999
***  Reaches in Subcatch 8
    RCHRES    601
    RCHRES     81
    RCHRES    602
    RCHRES     82
    RCHRES     83
***  Reaches in Subcatch 10
    RCHRES    603
***  Reaches in Subcatch 9
    RCHRES     91
    RCHRES     92
   END INGRP
END OPN SEQUENCE

GENER
 OPCODE
  #THRU#  OP-***
       CODE***
  10  200   24
 310  500   24
 510  700   18
 END OPCODE

 Point source flows are in Ml per year ***
 PARM
  # - # ***     K
***            West Rand consolidated
  10        3175.
***            Flip Human
  20        8035.
***            Randfontein East pumping
  30         365.
***            Randfontein East sewer
  40         365.
***            Cooke No. 2 WC
  50         900.
***            Bekkersdal WC
  60
***            Van Niekerk WC
  70        3300.
***            Venterspost pumping
  80        6650.
***            Harvey Watt shaft pumping
  90        3600.
***            West Driefontein pumping
 100       17800.
***            West Driefontein sewage
 110         400.
***            North Shaft pumping
 120        4000.
***            Elandsrand pumping
 130       16400.
***            Western Deep
 140        1240.
***            Blyvooruitzicht sewer
 150         730.
***            Blyvooruitzicht pumping
 160        1270.
***            Doornfontein pumping
 170        2500.
***            Doornfontein sewer
 180         615.
***            Khutsong sewer
 190
***            Welverdiend sewer
 200          73.

 310  500      500.
```

```
 END PARM

END GENER

PERLND
*** Pg. 300-456, 37-113, section 4.2(1)

 ACTIVITY
 *** Pg 302
  <PLS >       Active Sections (1=Active; 0=Inactive)          ***
  # - # ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC ***
  11  104          1               0
 END ACTIVITY

 PRINT-INFO
 *** Pg. 303-304
  <PLS >       Print-flags                          *** PIVL  PYR
  # - # ATMP SNOW PWAT  SED  PST  PWG PQAL MSTL PEST NITR PHOS TRAC      ***
 111  256          5                                  09
 END PRINT-INFO

 GEN-INFO
 *** Pg. 305-306
  <PLS ><-------Name-------->      Unit-systems   Printer ***
  # - #                        t-series Engl Metr ***
                               in  out        ***
  11   Catch 1 Non-cult            2   2   0  61
  12   Catch 1 Cult               2   2   0  61
  13   Catch 1 Urban              2   2   0  61
  14   Catch 1 Slimes             2   2   0  61
  21   Catch 2 Non-cult            2   2   0  61
  22   Catch 2 Cult               2   2   0  61
  23   Catch 2 Urban              2   2   0  61
  24   Catch 2 Slimes             2   2   0  61
  31   Catch 3 Non-cult            2   2   0  61
  32   Catch 3 Cult               2   2   0  61
  33   Catch 3 Urban              2   2   0  61
  34   Catch 3 Slimes             2   2   0  61
  41   Catch 4 Non-cult            2   2   0  61
  42   Catch 4 Cult               2   2   0  61
  43   Catch 4 Urban              2   2   0  61
  44   Catch 4 Slimes             2   2   0  61
  51   Catch 5 Non-cult            2   2   0  61
  52   Catch 5 Cult               2   2   0  61
  53   Catch 5 Urban              2   2   0  61
  54   Catch 5 Slimes             2   2   0  61
  61   Catch 6 Non-cult            2   2   0  61
  62   Catch 6 Cult               2   2   0  61
  63   Catch 6 Urban              2   2   0  61
  64   Catch 6 Slimes             2   2   0  61
  71   Catch 7 Non-cult            2   2   0  61
  72   Catch 7 Cult               2   2   0  61
  73   Catch 7 Urban              2   2   0  61
  74   Catch 7 Slimes             2   2   0  61
  81   Catch 8 Non-cult            2   2   0  61
  82   Catch 8 Cult               2   2   0  61
  83   Catch 8 Urban              2   2   0  61
  84   Catch 8 Slimes             2   2   0  61
  91   Catch 9 Non-cult            2   2   0  61
  92   Catch 9 Cult               2   2   0  61
  93   Catch 9 Urban              2   2   0  61
  94   Catch 9 Slimes             2   2   0  61
 101    Catch 10 Non-cult            2   2   0  61
 102    Catch 10 Cult               2   2   0  61
 103    Catch 10 Urban               2   2   0  61
 104    Catch 10 Slimes              2   2   0  61

 END GEN-INFO


 *** Section PWATER, Pg. 317-333, 54-74 ***

 PWAT-PARM1
 *** Pg. 318-319
  <PLS >  PWATER variable monthly parameter value flags ***
```

```
# - # CSNO RTOP UZFG  VCS  VUZ  VNN VIFW VIRC  VLE   ***
11       0   0   0   1   0   1   0   0   1
12       0   0   0   1   0   1   0   0   1
13       0   0   0   0   0   0   0   0   0
14       0   0   0   0   0   0   0   0   0
21  24   0   0   0   0   0   0   0   0   0
32       0   0   0   1   0   1   0   0   1
41  43   0   0   0   0   0   0   0   0   0
51       0   0   0   1   0   1   0   0   1
52       0   0   0   1   0   1   0   0   1
53       0   0   0   0   0   0   0   0   0
61 104   0   0   0   0   0   0   0   0   0
END PWAT-PARM1

PWAT-PARM2
*** Pg. 320-321
 <PLS > ***  PWATER input info: Part 2
 # - # ***FOREST    LZSN   INFILT    LSUR   SLSUR    KVARY    AGWRC
11  12   0.000   260.0    1.10    400.   0.010    0.0   0.995
13       0.000   250.0    1.00    400.   0.010    0.0   0.995
14       0.000   300.0    1.40    400.   0.010    0.0   0.995
21  24   0.000   260.0    1.10    400.   0.010    0.0   0.995
32       0.000   250.0    1.10    400.   0.010    0.0   0.995
41  44   0.000   260.0    1.10    400.   0.010    0.0   0.995
51  53   0.000   260.0    1.10    400.   0.010    0.0   0.995
61 104   0.000   260.0    1.10    400.   0.010    0.0   0.995
END PWAT-PARM2

PWAT-PARM3
*** Pg. 322-323
 <PLS > ***  PWATER input info: Part 3
 # - # ***PETMAX   PETMIN   INFEXP   INFILD   DEEPFR   BASETP   AGWETP
11  14                2.0     2.0    0.00     0.0     0.00
21  24                2.0     2.0    0.05     0.0     0.00
31  33                2.0     2.0    0.50     0.0     0.00
41  43                2.0     2.0    0.00     0.0     0.00
51  53                2.0     2.0    0.00     0.0     0.00
61  64                2.0     2.0    0.95     0.0     0.00
71  74                2.0     2.0    0.95     0.0     0.00
81  84                2.0     2.0    0.95     0.0     0.00
91  94                2.0     2.0    0.95     0.0     0.00
101 104               2.0     2.0    0.95     0.0     0.00
END PWAT-PARM3

PWAT-PARM4
*** Pg. 323-324
 <PLS >    PWATER input info: Part 4                   ***
 # - #    CEPSC    UZSN    NSUR    INTFW     IRC    LZETP ***
11  24    1.05     3.0     0.4     1.5     0.60    .30
32        1.05     3.0     0.4     1.5     0.60    .30
41  44    1.05     3.0     0.4     1.5     0.60    .30
51  53    1.05     3.0     0.4     1.5     0.60    .30
61 104    1.05     3.0     0.4     1.5     0.60    .30
END PWAT-PARM4

PWAT-PARM5 Defaults used ***
*** Pg. 325

MON-INTERCEP
 <PLS>   Only required if VCSFG=1 in PWAT-PARM1(ACRU-RE Schulze     ***
 # - #  Interception storage capacity at start of each month(mm)   ***
       JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC ***
11     1.4 1.5 1.5 1.4 1.3 1.3 1.3 1.3 1.5 1.4 1.4 1.4
12     1.4 1.5 1.5 0.4 0.3 0.3 0.3 0.3 0.5 1.0 1.4 1.4
32     1.4 1.5 1.5 0.4 0.3 0.3 0.3 0.3 0.5 1.0 1.4 1.4
52     1.4 1.5 1.5 0.4 0.3 0.3 0.3 0.3 0.5 1.0 1.4 1.4
END MON-INTERCEP

MON-MANNING
 <PLS >  Only required if VNNFG=1 in PWAT-PARM1                     ***
 # - #  Manning's n for overland flow at start of each month(Non-D)***
       JAN  FEB  MAR  APR  MAY  JUN  JUL  AUG  SEP  OCT  NOV  DEC ***
11     .050 .050 .050 .050 .085 .085 .085 .085 .085 .085 .050 .050
12     .050 .050 .050 .050 .085 .085 .085 .085 .085 .085 .050 .050
32     .050 .050 .050 .050 .085 .085 .085 .085 .085 .085 .050 .050
```

```
52     .050 .050 .050 .050 .085 .085 .085 .085 .085 .085 .050 .050
END MON-MANNING

MON-LZETPARM
  <PLS > Only required if VLEFG=1 in PWAT-PARM1                ***
  # - # Lower Zone ET Parameter at start of each month          ***
        JAN FEB MAR APR MAY JUN JUL AUG SEP OCT NOV DEC ***
 11     0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30 0.30
 12     0.30 0.30 0.30 0.20 0.20 0.20 0.20 0.20 0.23 0.25 0.30 0.30
 32     0.40 0.40 0.30 0.20 0.20 0.20 0.20 0.20 0.23 0.25 0.30 0.40
 51     0.40 0.40 0.30 0.20 0.20 0.20 0.20 0.20 0.23 0.25 0.30 0.40
 52     0.40 0.40 0.30 0.20 0.20 0.20 0.20 0.20 0.23 0.25 0.30 0.40
END MON-LZETPARM

PWAT-STATE1
*** Pg. 323-324
  <PLS > *** Initial conditions at start of simulation
  # - # *** CEPS    SURS    UZS    IFWS    LZS    AGWS    GWVS
 11  14    0.00    0.0     1.     0.0    180.0   10.0    00.
 21 104    0.00    0.0     1.     0.0    180.0   10.0    00.
END PWAT-STATE1

"GENERAL QUALITY" Section, pg. 363-375, 84-89 ***

NQUALS
*** Pg. 364
  <PLS >    ***
  #   #NQUAL***
 11 104   1
END NQUALS

Data for first general quality constituent.  In the RCHRES module    ***
treated as a conservative                                    ***

QUAL-PROPS
*** Pg. 366-367
  #   #<--QUALID-->  QTID QSD VPFW VPFS QSO VQO QIFW VIQC QAGW VAQC ***
 11 104 TDS          kg  0  0  0  1  0  1  0  1  0
END QUAL-PROPS

QUAL-INPUT
*** Pg. 368-369
  <PLS >                      Concs below are kg/l          ***
  # - #   SQO  POTFW  POTFS  ACQOP  SQOLIM  WSQOP  IOQC  AOQC***
 11 104                 0.3    3.0    42. 7.5E-05 2.5E-05
END QUAL-INPUT

END PERLND

RCHRES
*** Pg. 489-612, 128-259, section 4.2(3)

ACTIVITY
*** Pg. 489-490
  RCHRES  Active Sections (1=Active; 0=Inactive)         ***
  # - # HYFG ADFG CNFG HTFG SDFG GQFG OXFG NUFG PKFG PHFG ***
 11 999   1  0  0
END ACTIVITY

PRINT-INFO
*** Pg. 491-492
        Print-flags                                   ***
  # - # HYDR ADCA CONS HEAT  SED  GQL OXRX NUTR PLNK  PH     PYR ***
 11 999   5  5  5                    09
END PRINT-INFO

GEN-INFO
*** Pg. 493-494
  RCHRES<-------Name------->Nexit  Unit Systems  Printer    ***
  # - #                    User t-series  Engl Metr LKFG ***
                             in  out                ***
 11    Tudor+Lancaster      1       2  2  0  62  1
 12    Tudor to Luipaards   1       2  2  0  62  0
 13    Luipaardsvlei        1       2  2  0  62  1
 21    Luipaards to Donald  1       2  2  0  62  0
```

```
22    Donaldson dam         2       2  2   0  62   1
31    Kocksoordspruit       1       2  2   0  62   0
41    Middelvleispruit      1       2  2   0  62   0
51    Rietfonteinspruit     1       2  2   0  62   0
61    WFS to C2H056         1       2  2   0  62   0
71    WFS to C2H032         1       2  2   0  62   0
81    Harry's Dam           1       2  2   0  62   1
82    WFS to Padda Dam      1       2  2   0  62   0
83    Paddadam              1       2  2   0  62   1
91    Paddadam to Welver/d  1       2  2   0  62   0
92    Welver/d C2H069       1       2  2   0  62   1
601   W.Drief/c C2H045/63   1       2  2   0  62   0
602   WFS cleanw/c C2H030   1       2  2   0  62   0
603   Welverd/c to C2H060   1       2  2   0  62   0
999   1m pipeline           1       2  2   0  62   0
END GEN-INFO

HYDR-PARM1
*** Pg. 496-497, 132-148
 RCHRES  Flags for HYDR section                       ***
 # - #  VC A1 A2 A3  ODFVFG for each     ODGTFG for each *** FUNCT  for each
        FG FG FG FG  possible   exit    possible   exit *** possible   exit
           1 2 3   1 2 3 4 5      1 2 3 4 5 ***   1 2 3 4 5
 11  21  0 1 1 1    4
 22      0 1 1 1    4 5
 31 999  0 1 1 1    4
END HYDR-PARM1

HYDR-PARM2
*** Pg. 498-499
 RCHRES ***
 # - #   FTABNO      LEN     DELTH     STCOR       KS      DB50 ***
 *** The values of DB50 are needed by the Colby and Toffaleti sediment
 *** transport methods.  We will use the default (0.25mm)
 11         20      3.
 12         20      15.
 13         20      1.
 21         20      10.
 22        120      3.
 31         40      2.
 41         40      5.
 51         40      6.
 61         50      7.
 71         60      5.
 81         70      10.
 82         70      5.
 83        160      2.
 91        160      10.
 92        160      1.
601        110      10.
602        110      10.
603        110      18.
999        130      26.
END HYDR-PARM2

HYDR-INIT
*** Pg. 501
 RCHRES ***
 # - #      VOL ***
 Reaches are assumed initially empty ***
 11 999     0.0
END HYDR-INIT

Conservative substances, pg 515-519, 156-160 ***

*** Table NCONS not required, since only one conservative substance
*** is being simulated

CONS-DATA
*** Pg. 518-519
 RCHRES          ***
 # - #      Substance-id     Conc       ID      CONV     QTYID ***
 11 999   TDS                150.     mg/l    1000.       kg
END CONS-DATA
```

```
END RCHRES

*** FTABLES - see pg 642-644, 137-138

FTABLES

 FTABLE    10
 ROWS COLS ***
  20   4
   DEPTH     AREA   VOLUME    DISCH  FLO-THRU ***
    ( m)  (  HA)    (Mm3)    (CMS)    (MIN) ***
    .000    .000   .0000     .000     0.0
    .250    .056    .000     .060    19.67
    .500    .113    .000     .379    12.39
    .750    .169    .001    1.117     9.45
    .850    .249    .001    1.488     9.44
    .950    .329    .001    2.102     8.96
   1.050    .409    .002    2.984     8.39
   1.150    .490    .002    4.171     7.80
   1.250    .570    .002    5.698     7.26
   1.350    .650    .003    7.604     6.77
   1.550    .810    .005   12.688     5.96
   1.750    .971    .006   19.695     5.36
   1.950   1.131    .008   28.879     4.87
   2.350   1.339    .013   59.680     3.73
   2.750   1.547    .019  101.110     3.16
   3.150   1.755    .026  153.977     2.79
   3.550   1.963    .033  219.049     2.52
   3.950   2.171    .041  297.083     2.33
   4.350   2.379    .051  388.823     2.17
   4.750   2.587    .060  495.004     2.04
 END FTABLE 10

 FTABLE    20
 ROWS COLS ***
  20   4
   DEPTH     AREA   VOLUME    DISCH  FLO-THRU ***
    ( m)  (  HA)    (Mm3)    (CMS)    (MIN) ***
    .000    .000   .0000     .000     0.0
    .250    .043    .000     .007   135.63
    .500    .087    .000     .042    85.42
    .750    .130    .000     .125    65.18
    .875    .158    .001     .189    58.76
   1.000    .186    .001     .275    53.44
   1.125    .214    .001     .385    49.03
   1.250    .243    .001     .522    45.34
   1.375    .271    .002     .687    42.22
   1.500    .299    .002     .883    39.56
   1.750    .355    .003    1.378    35.25
   2.000    .412    .004    2.023    31.91
   2.250    .468    .005    2.834    29.25
   2.750   4.801    .018   12.215    24.76
   3.250   9.135    .053   51.909    17.01
   3.750  13.468    .109  140.114    13.02
   4.250  17.801    .188  291.850    10.72
   4.750  22.135    .288  520.486     9.21
   5.250  26.468    .409  838.297     8.13
   5.750  30.801    .552 1256.757     7.32
 END FTABLE 20

 FTABLE    30
 ROWS COLS ***
  20   4
   DEPTH     AREA   VOLUME    DISCH  FLO-THRU ***
    ( m)  (  HA)    (Mm3)    (CMS)    (MIN) ***
    .000    .000   .0000     .000     0.0
    .250    .133    .000     .032    87.59
    .500    .267    .001     .201    55.17
    .750    .400    .002     .594    42.09
    .858    .455    .002     .852    38.39
    .967    .510    .002    1.169    35.43
   1.075    .565    .003    1.550    33.00
   1.183    .620    .004    1.997    30.96
   1.292    .675    .004    2.517    29.21
   1.400    .730    .005    3.114    27.69
```

```
  1.617   .840   .007   4.550   25.18
  1.833   .950   .009   6.339   23.17
  2.050   1.060   .011   8.510   21.52
  2.483   3.536   .021   17.507   19.94
  2.917   6.012   .042   37.884   18.32
  3.350   8.489   .073   75.603   16.11
  3.783   10.965   .115  135.598   14.16
  4.217   13.441   .168  222.265   12.60
  4.650   15.917   .232  339.650   11.37
  5.083   18.393   .306  491.538   10.38
END FTABLE 30

FTABLE   40
ROWS COLS ***
 20   4
  DEPTH    AREA   VOLUME    DISCH  FLO-THRU ***
  ( m)  (  HA)   (Mm3)    (CMS)    (MIN) ***
  .000    .000   .0000    .000    0.0
  .250   15.547   .019   1.011   320.29
  .500   31.093   .078   6.422   201.73
  .750   46.640   .175   18.938   153.92
  .875   52.753   .237   28.952   136.44
  1.000   58.867   .307   41.371   123.59
  1.125   64.980   .384   56.358   113.62
  1.250   71.093   .469   74.076   105.57
  1.375   77.207   .562   94.685   98.91
  1.500   83.320   .662  118.343   93.27
  1.750   95.547   .886  175.414   84.17
  2.000  107.773   1.140  246.487   77.08
  2.250  120.000   1.425  332.713   71.37
  2.750  200.000   2.225  614.272   60.36
  3.250  280.000   3.425 1026.303   55.62
  3.750  360.000   5.025 1608.083   52.08
  4.250  440.000   7.025 2392.493   48.94
  4.750  520.000   9.425 3409.195   46.07
  5.250  600.000  12.225 4685.722   43.48
  5.750  680.000  15.425 6248.035   41.15
END FTABLE 40

FTABLE   50
ROWS COLS ***
 20   4
  DEPTH    AREA   VOLUME    DISCH  FLO-THRU ***
  ( m)  (  HA)   (Mm3)    (CMS)    (MIN) ***
  .000    .000   .0000    .000    0.0
  .250   6.533   .008    .389   349.80
  .500   13.067   .033   2.471   220.31
  .750   19.600   .073   7.287   168.10
  .875   25.083   .101   10.576   159.84
  1.000   30.567   .136   15.155   149.80
  1.125   36.050   .178   21.177   139.96
  1.250   41.533   .226   28.802   130.97
  1.375   47.017   .282   38.185   122.94
  1.500   52.500   .344   49.476   115.84
  1.750   63.467   .489   78.363   103.97
  2.000   74.433   .661  116.580   94.53
  2.250   85.400   .861  165.184   86.87
  2.750  102.900   1.332  327.671   67.74
  3.250  120.400   1.890  549.036   57.37
  3.750  137.900   2.536  837.412   50.47
  4.250  155.400   3.269 1199.944   45.40
  4.750  172.900   4.090 1643.322   41.48
  5.250  190.400   4.998 2173.927   38.32
  5.750  207.900   5.994 2797.892   35.70
END FTABLE 50

FTABLE   60
ROWS COLS ***
 20   4
  DEPTH    AREA   VOLUME    DISCH  FLO-THRU ***
  ( m)  (  HA)   (Mm3)    (CMS)    (MIN) ***
  .000    .000   .0000    .000    0.0
  .250   3.600   .004    .308   243.22
  .500   7.200   .018   1.958   153.18
  .750   10.800   .041   5.775   116.88
```

```
  .875  16.300   .057   7.863  121.75
 1.000  21.800   .081  11.550  117.24
 1.125  27.300   .112  16.962  109.99
 1.250  32.800   .150  24.314  102.48
 1.375  38.300   .194  33.838   95.52
 1.500  43.800   .245  45.762   89.32
 1.750  54.800   .368  77.700   79.04
 2.000  65.800   .519 121.826   71.04
 2.250  76.800   .697 179.738   64.68
 2.750 122.954  1.197 368.078   51.40
 3.250 169.108  1.927 712.885   45.05
 3.750 215.262  2.888 1188.250  40.51
 4.250 261.415  4.080 1842.985  36.89
 4.750 307.569  5.502 2703.216  33.92
 5.250 353.723  7.155 3793.269  31.44
 5.750 399.877  9.039 5136.117  29.33
END FTABLE 60

FTABLE    70
ROWS COLS ***
 20   4
  DEPTH     AREA   VOLUME    DISCH  FLO-THRU ***
  ( m)   (  HA)   (Mm3)    (CMS)     (MIN) ***
  .000    .000   .0000    .000     0.0
  .250    .723    .001    .113   133.56
  .500   1.447    .004    .717    84.12
  .750   2.170    .008   1.113    64.18
  .792   3.973    .009   1.816    86.41
  .833   5.775    .011   1.966    97.05
  .875   7.577    .014   2.361   100.45
  .917   9.380    .018   2.967    99.79
  .958  11.162    .022   3.785    97.07
 1.000  12.985    .027   4.830    93.45
 1.083  16.590    .039   7.670    85.63
 1.167  20.195    .055  11.638    78.38
 1.250  23.800    .073  16.888    72.10
 1.417  31.092    .119  35.387    55.95
 1.583  38.383    .177  61.265    48.07
 1.750  45.675    .247  95.629    43.00
 1.917  52.967    .329 139.455    39.31
 2.083  60.258    .423 193.654    36.43
 2.250  67.550    .530 259.095    34.08
 2.417  74.842    .648 336.611    32.11
END FTABLE 70

FTABLE    80
ROWS COLS ***
 20   4
  DEPTH     AREA   VOLUME    DISCH  FLO-THRU ***
  ( m)   (  HA)   (Mm3)    (CMS)     (MIN) ***
  .000    .000   .0000    .000     0.0
  .250    .800    .001    .036   464.71
  .500   1.600    .004    .228   292.68
  .750   2.400    .009    .672   223.33
  .858   8.733    .015    .704   356.09
  .967  15.067    .028   1.385   335.95
 1.075  21.400    .048   2.684   296.06
 1.183  27.733    .074   4.739   261.29
 1.292  34.067    .108   7.690   233.57
 1.400  40.400    .148  11.670   211.51
 1.617  53.067    .249  23.213   179.03
 1.833  65.733    .378  40.301   156.35
 2.050  78.400    .534  63.792   139.57
 2.483 113.067    .949 149.806   105.59
 2.917 147.733   1.514 281.569    89.62
 3.350 182.400   2.229 469.547    79.13
 3.783 217.067   3.095 722.771    71.37
 4.217 251.733   4.111 1049.535   65.28
 4.650 286.400   5.277 1457.630   60.33
 5.083 321.067   6.593 1954.457   56.22
END FTABLE 80

FTABLE    110
Canals ***
ROWS COLS ***
```

```
  5   4
   DEPTH     AREA   VOLUME    DISCH ***
    ( m)  (  HA)    (Mm3)    (CMS) ***
    .000    .000    .0000     .000
   0.500    0.8     .006     3.000
   1.000    1.8     .018     7.300
   5.000    6.8    1.000   100.00
  10.000   20.0    4.000   500.00
 END FTABLE110

 FTABLE   120
 Donaldson Dam ***
ROWS COLS ***
  6   5
   DEPTH     AREA   VOLUME    DISCH    DISCH ***
    ( m)  (  HA)    (Mm3)    (CMS)    (CMS) ***
    .000    .000    .0000     .000     0.0
   2.000    10.0    .1000     1.0      0.0
   5.000    40.0    .3000     1.0      0.0
   7.000    80.0    .4600     1.0      0.0
  10.000    90.0    .8000     1.0     30.0
  15.000   100.0   1.5000     1.0    100.0
 END FTABLE120

 FTABLE   130
 1m pipeline ***
ROWS COLS ***
  6   4
   DEPTH     AREA   VOLUME    DISCH ***
    ( m)  (  HA)    (Mm3)    (CMS) ***
    .000    .000    .0000     .000
    .250    1.80    .007      .350
    .500    2.60   0.0102     .500
    .750    1.80   0.0170     .850 ***
   1.000    .0005   0.0204     1.0 ***
   1.500    .0001   0.0205    20.0 ***
    .750    3.80   0.0170     .850
   1.000    5.00   0.0204     1.0
   1.500   10.00   0.0300    20.0
 END FTABLE130

 FTABLE   160
 Padda and Welverdiend Dams ***
ROWS COLS ***
  6   4
   DEPTH     AREA   VOLUME    DISCH ***
    ( m)  (  HA)    (Mm3)    (CMS) ***
    .000    .000    .0000     .000
   2.000           .0500    1.0
   5.000           .1500    1.0
   7.000           .2300    1.0
  10.000           .4000   15.0
  15.000          0.7500  150.0
 END FTABLE160

END FTABLES

*** For an understanding of EXT SOURCES, EXT TARGETS, SCHEMATIC, MASS-LINK
*** and NETWORK blocks, the user should be familiar with the Time
*** Series Linkages (pg. 645-667) and the Time Series Catalog (pg. 668-724)

EXT SOURCES
*** Pg. 649-651
<-Volume-> <Member> SsysSgap<--Mult-->Tran <-Target vols> <-Grp> <-Member-> ***
<Name>   # <Name> # tem strg<-factor->strg <Name>   #  #       <Name> # # ***

Get total daily A-pan evap ***
WDM     1 EVAP   3 METR     0.80       PERLND  11 104 EXTNL  PETINP

Get total daily precip ***
WDM    14 PRCP   3 METR                PERLND  11     EXTNL  PREC
WDM    14 PRCP   3 METR                PERLND  12     EXTNL  PREC
WDM    14 PRCP   3 METR                PERLND  13     EXTNL  PREC
WDM    14 PRCP   3 METR                PERLND  14     EXTNL  PREC
WDM    14 PRCP   3 METR                PERLND  21     EXTNL  PREC
```

```
WDM   14 PRCP  3 METR          PERLND 22   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 23   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 24   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 31   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 32   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 33   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 41   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 42   EXTNL PREC
WDM   14 PRCP  3 METR          PERLND 43   EXTNL PREC
WDM   14 PRCP  3 METR  0.7      PERLND 51   EXTNL PREC
WDM   14 PRCP  3 METR  0.7      PERLND 52   EXTNL PREC
WDM   14 PRCP  3 METR  0.7      PERLND 53   EXTNL PREC
WDM   14 PRCP  3 METR  0.5      PERLND 61   EXTNL PREC
WDM   14 PRCP  3 METR  0.5      PERLND 62   EXTNL PREC
WDM   14 PRCP  3 METR  0.5      PERLND 63   EXTNL PREC
WDM   14 PRCP  3 METR  0.5      PERLND 64   EXTNL PREC
WDM   14 PRCP  3 METR  0.25     PERLND 71   EXTNL PREC
WDM   14 PRCP  3 METR  0.25     PERLND 72   EXTNL PREC
WDM   14 PRCP  3 METR  0.25     PERLND 73   EXTNL PREC
WDM   14 PRCP  3 METR  0.25     PERLND 74   EXTNL PREC

WDM   19 PRCP  3 METR  0.5      PERLND 61   EXTNL PREC
WDM   19 PRCP  3 METR  0.5      PERLND 62   EXTNL PREC
WDM   19 PRCP  3 METR  0.5      PERLND 63   EXTNL PREC
WDM   19 PRCP  3 METR  0.5      PERLND 64   EXTNL PREC
WDM   19 PRCP  3 METR  0.75     PERLND 71   EXTNL PREC
WDM   19 PRCP  3 METR  0.75     PERLND 72   EXTNL PREC
WDM   19 PRCP  3 METR  0.75     PERLND 73   EXTNL PREC
WDM   19 PRCP  3 METR  0.75     PERLND 74   EXTNL PREC

WDM   17 PRCP  3 METR  0.4 ***  PERLND 51   EXTNL PREC
WDM   17 PRCP  3 METR  0.4 ***  PERLND 52   EXTNL PREC
WDM   17 PRCP  3 METR  0.4 ***  PERLND 53   EXTNL PREC
WDM   17 PRCP  3 METR          PERLND 81   EXTNL PREC
WDM   17 PRCP  3 METR          PERLND 82   EXTNL PREC
WDM   17 PRCP  3 METR          PERLND 83   EXTNL PREC
WDM   17 PRCP  3 METR          PERLND 84   EXTNL PREC

WDM   18 PRCP  3 METR          PERLND 91   EXTNL PREC
WDM   18 PRCP  3 METR          PERLND 92   EXTNL PREC
WDM   18 PRCP  3 METR          PERLND 93   EXTNL PREC
WDM   18 PRCP  3 METR          PERLND 94   EXTNL PREC

WDM   12 PRCP  3 METR          PERLND 101  EXTNL PREC
WDM   12 PRCP  3 METR          PERLND 102  EXTNL PREC
WDM   12 PRCP  3 METR          PERLND 103  EXTNL PREC
WDM   12 PRCP  3 METR          PERLND 104  EXTNL PREC

END EXT SOURCES

SCHEMATIC
*** Pg. 654-658
<-Source->          <--Area-->    <-Target->  <ML-> ***
<Name>  #           <-factor->    <Name>  #    #  ***
             (ha)                   ***
PERLND 11              7698.0     RCHRES 12    1
PERLND 12               105.0     RCHRES 12    1
PERLND 13               327.0     RCHRES 11    1
PERLND 14               470.0     RCHRES 11    1

PERLND 21              4309.0     RCHRES 21    1
PERLND 22              4338.0     RCHRES 21    1
PERLND 23               368.0     RCHRES 21    1
PERLND 24               191.0     RCHRES 21    1

PERLND 32               400.0     RCHRES 31    1

PERLND 41              1746.0     RCHRES 41    1
PERLND 42               448.0     RCHRES 41    1
PERLND 43               406.0     RCHRES 41    1

PERLND 51               800.0     RCHRES 51    1
PERLND 52              1300.0     RCHRES 51    1
PERLND 53              1000.0     RCHRES 51    1
```

```
PERLND 61     15808.0   RCHRES 61    1
PERLND 62      9268.0   RCHRES 61    1
PERLND 63      1163.0   RCHRES 61    1
PERLND 64       296.0   RCHRES 61    1

PERLND 71     21800.0   RCHRES 71    1
PERLND 72     20238.0   RCHRES 71    1
PERLND 73        91.0   RCHRES 71    1
PERLND 74       195.0   RCHRES 71    1

PERLND 81      5881.0   RCHRES 82    1
PERLND 82      1056.0   RCHRES 82    1
PERLND 83       248.0   RCHRES 82    1
PERLND 84       144.0   RCHRES 82    1

PERLND 91     10743.0   RCHRES 91    1
PERLND 92     10568.0   RCHRES 91    1
PERLND 93       726.0   RCHRES 91    1
PERLND 94       370.0   RCHRES 91    1

PERLND 101     1964.0   RCHRES 91    1
PERLND 102     7403.0   RCHRES 91    1
PERLND 103      110.0   RCHRES 91    1
PERLND 104      653.0   RCHRES 91    1

GENER  10               RCHRES 12    5
GENER  20               RCHRES 12    5
GENER  30               RCHRES 12    5
GENER  40               RCHRES 12    5
GENER  50               RCHRES 22    5
GENER  60               RCHRES 22    5
GENER  70               RCHRES 999   5
GENER  80               RCHRES 999   5
GENER  90               RCHRES 999   5
GENER  100              RCHRES 601   5
GENER  110              RCHRES 601   5
GENER  120              RCHRES 602   5
GENER  130              RCHRES 91    5
GENER  140              RCHRES 603   5
GENER  150              RCHRES 603   5
GENER  160              RCHRES 603   5
GENER  170              RCHRES 603   5
GENER  180              RCHRES 603   5
GENER  190              RCHRES 91    5
GENER  200              RCHRES 91    5

GENER  510              RCHRES 12    6
GENER  520              RCHRES 12    6
GENER  530              RCHRES 12    6
GENER  540              RCHRES 12    6
GENER  550              RCHRES 22    6
GENER  560              RCHRES 22    6
GENER  570              RCHRES 999   6
GENER  580              RCHRES 999   6
GENER  590              RCHRES 999   6
GENER  600              RCHRES 601   6
GENER  610              RCHRES 601   6
GENER  620              RCHRES 602   6
GENER  630              RCHRES 91    6
GENER  640              RCHRES 603   6
GENER  650              RCHRES 603   6
GENER  660              RCHRES 603   6
GENER  670              RCHRES 603   6
GENER  680              RCHRES 603   6
GENER  690              RCHRES 91    6
GENER  700              RCHRES 91    6

RCHRES 11               RCHRES 12    2
RCHRES 12               RCHRES 13    2
RCHRES 13               RCHRES 21    2
RCHRES 21               RCHRES 22    2
RCHRES 31               RCHRES 41    2
RCHRES 41               RCHRES 61    2
RCHRES 51               RCHRES 61    2
*** Donaldson dam into WFS
```

```
RCHRES  22                    RCHRES  61.    4
*** Donaldson dam into pipe
RCHRES  22                    RCHRES 999     3
RCHRES  61                    RCHRES  71     2
RCHRES 601                    RCHRES  81     2
RCHRES  71                    RCHRES  81     2
RCHRES 999                    RCHRES  81     2
RCHRES  81                    RCHRES  82     2
RCHRES 602                    RCHRES  83     2
RCHRES  82                    RCHRES  83     2
RCHRES  83                    RCHRES  91     2
RCHRES 603                    RCHRES  91     2
RCHRES  91                    RCHRES  92     2

END SCHEMATIC

MASS-LINK
*** Pg. 659-660

 MASS-LINK      1
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***
             Factor converts (mm.ha) to (million m3)          ***
PERLND    PWATER PERO       .00001      RCHRES        INFLOW IVOL
PERLND    PQUAL  POQUAL                 RCHRES        INFLOW ICON  1
 END MASS-LINK   1

 MASS-LINK      2
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***
RCHRES    ROFLOW                        RCHRES        INFLOW
 END MASS-LINK   2

 MASS-LINK      3
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***
Outflow into pipeline                                 ***
RCHRES    OFLOW  OVOL  1                RCHRES        INFLOW IVOL  1 1
RCHRES    OFLOW  OCON  1                RCHRES        INFLOW ICON  1
 END MASS-LINK   3

 MASS-LINK      4
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***
Outflow into Wonderfontein                            ***
RCHRES    OFLOW  OVOL  2                RCHRES        INFLOW IVOL  1 1
RCHRES    OFLOW  OCON  1                RCHRES        INFLOW ICON  1
 END MASS-LINK   4

 MASS-LINK      5
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***
The conversion factor converts from Ml/day to Mm3/day          ***
Need to change if changing simulation timestep !!!!            ***
GENER     OUTPUT TIMSER    2.74E-6      RCHRES        INFLOW IVOL  1 1
 END MASS-LINK   5

 MASS-LINK      6
<Srce>    <-Grp> <-Member-><--Mult-->   <Targ>        <-Grp> <-Member-> ***
<Name>    <Name> <Name> # #<-factor->   <Name>        <Name> <Name> # # ***

Need to change if changing simulation timestep !!!!            ***
The multiplication factor converts from Ml/year * mg/l to kg/day    ***
GENER     OUTPUT TIMSER    0.00274      RCHRES        INFLOW ICON  1
 END MASS-LINK   6

END MASS-LINK

NETWORK
<-Volume-> <-Grp> <-Member-><--Mult-->Tran <-Target vols> <-Grp> <-Member->  ***
<Name>   #       <Name> # #<-factor->strg <Name>   #   #      <Name> # #  ***

GENER   10 OUTPUT TIMSER                GENER  510    INPUT  ONE
GENER   20 OUTPUT TIMSER                GENER  520    INPUT  ONE
GENER   30 OUTPUT TIMSER                GENER  530    INPUT  ONE
```

```
GENER  40 OUTPUT TIMSER           GENER 540   INPUT  ONE
GENER  50 OUTPUT TIMSER           GENER 550   INPUT  ONE
GENER  60 OUTPUT TIMSER           GENER 560   INPUT  ONE
GENER  70 OUTPUT TIMSER           GENER 570   INPUT  ONE
GENER  80 OUTPUT TIMSER           GENER 580   INPUT  ONE
GENER  90 OUTPUT TIMSER           GENER 590   INPUT  ONE
GENER 100 OUTPUT TIMSER           GENER 600   INPUT  ONE
GENER 110 OUTPUT TIMSER           GENER 610   INPUT  ONE
GENER 120 OUTPUT TIMSER           GENER 620   INPUT  ONE
GENER 130 OUTPUT TIMSER           GENER 630   INPUT  ONE
GENER 140 OUTPUT TIMSER           GENER 640   INPUT  ONE
GENER 150 OUTPUT TIMSER           GENER 650   INPUT  ONE
GENER 160 OUTPUT TIMSER           GENER 660   INPUT  ONE
GENER 170 OUTPUT TIMSER           GENER 670   INPUT  ONE
GENER 180 OUTPUT TIMSER           GENER 680   INPUT  ONE
GENER 190 OUTPUT TIMSER           GENER 690   INPUT  ONE
GENER 200 OUTPUT TIMSER           GENER 700   INPUT  ONE

GENER 310 OUTPUT TIMSER           GENER 510   INPUT  TWO
GENER 320 OUTPUT TIMSER           GENER 520   INPUT  TWO
GENER 330 OUTPUT TIMSER           GENER 530   INPUT  TWO
GENER 340 OUTPUT TIMSER           GENER 540   INPUT  TWO
GENER 350 OUTPUT TIMSER           GENER 550   INPUT  TWO
GENER 360 OUTPUT TIMSER           GENER 560   INPUT  TWO
GENER 370 OUTPUT TIMSER           GENER 570   INPUT  TWO
GENER 380 OUTPUT TIMSER           GENER 580   INPUT  TWO
GENER 390 OUTPUT TIMSER           GENER 590   INPUT  TWO
GENER 400 OUTPUT TIMSER           GENER 600   INPUT  TWO
GENER 410 OUTPUT TIMSER           GENER 610   INPUT  TWO
GENER 420 OUTPUT TIMSER           GENER 620   INPUT  TWO
GENER 430 OUTPUT TIMSER           GENER 630   INPUT  TWO
GENER 440 OUTPUT TIMSER           GENER 640   INPUT  TWO
GENER 450 OUTPUT TIMSER           GENER 650   INPUT  TWO
GENER 460 OUTPUT TIMSER           GENER 660   INPUT  TWO
GENER 470 OUTPUT TIMSER           GENER 670   INPUT  TWO
GENER 480 OUTPUT TIMSER           GENER 680   INPUT  TWO
GENER 490 OUTPUT TIMSER           GENER 690   INPUT  TWO
GENER 500 OUTPUT TIMSER           GENER 700   INPUT  TWO
END NETWORK

EXT TARGETS
*** Pg. 661-663
<-Volume-> <-Grp> <-Member-><--Mult-->Tran <-Volume-> <Member> Tsys Aggr Amd ***
<Name>  #      <Name> # #<-factor->strg <Name>   # <Name>qf  tem strg strg***

*** For selected reaches, we output the following simulated time series:
*** Total outflow rate (m3/s)

RCHRES  13 HYDR   RO              WDM   801 HYDR  1 METR AGGR REPL
RCHRES  22 HYDR   O    1          WDM   802 HYDR  1 METR AGGR REPL
RCHRES  22 HYDR   O    2          WDM   803 HYDR  1 METR AGGR REPL
RCHRES  31 HYDR   RO              WDM   804 HYDR  1 METR AGGR REPL
RCHRES  41 HYDR   RO              WDM   805 HYDR  1 METR AGGR REPL
RCHRES  51 HYDR   RO              WDM   806 HYDR  1 METR AGGR REPL
RCHRES  61 HYDR   RO              WDM   807 HYDR  1 METR AGGR REPL
RCHRES  81 HYDR   RO              WDM   808 HYDR  1 METR AGGR REPL
RCHRES  92 HYDR   RO              WDM   809 HYDR  1 METR AGGR REPL
RCHRES 601 HYDR   RO              WDM   810 HYDR  1 METR AGGR REPL
RCHRES 602 HYDR   RO              WDM   811 HYDR  1 METR AGGR REPL
RCHRES 603 HYDR   RO              WDM   812 HYDR  1 METR AGGR REPL

END EXT TARGETS

END RUN
```