Towards the Resource Directed Measures: Groundwater Component (Version 1.1)

By

Y Xu[1*], C Colvin[2], GJ van Tonder[3], S Hughes[2],
D le Maitre[2], J Zhang[2], T Mafanya[1] and E Braune[4]

[1] Department of Earth Sciences at the University of the Western Cape, Bellville
[2] Environmentek, CSIR, Stellenbosch
[3] Institute for Groundwater Studies at the University of the Free State, Bloemfontein
[4] Directorate of Geohydrology, Department of Water Affairs & Forestry, Pretoria

FINAL REPORT

prepared for the

Water Research Commission

on Projects K5/1090, 1091 & 1092

WRC Report No. 1090-2/1/03
ISBN No. 1-77005-022-1

May 2003

Disclaimer

Printed by Silowa Printers

Contents

List of Figures

List of Tables

Executive Summary

The National Water Act of 1998 places an emphasis on the protection of water resources for their sustainable utilisation. This is reflected in the subsequent development of Resource Directed Measures (RDM), which consists of three important aspects, namely: classification; the reserve; and resource quality objectives.

The purpose of the Version 1.1 report is to provide the technical reader with the best available information regarding an approach for determination of the groundwater component of the RDM as required for issuing licenses for water use.

As a core concept of the RDM, the Reserve covers both Basic Human Needs (BHN) and Ecological Reserve (ER). Since October 1st, 1999, a Reserve determination of the total water resource should be undertaken if a license application for water allocation is processed. Determination of the Reserve for aquatic ecosystems entails investigation of the relationship of major interactive components of the hydrologic cycle, namely groundwater and surface water bodies including rivers, lakes and estuaries. Depending upon the current stress on the resource in question, the Reserve determination required may be a rapid or intermediate estimate, or a comprehensive evaluation.

As part of the RDM, this draft of the final report is based on the research findings of programme entitled "Groundwater Reserve Determination", sponsored by the Water Research Commission (WRC). The Programme started on January 1st, 1999 and is completed by the end of 2001.

This documentation presents a recommended approach to classify groundwater resources under the NWA, and set the Reserve and Resource Quality Objectives.

Background

For purpose of groundwater protection, all three mechanisms of the RDM, namely Classification, Setting of the Reserve and Resource Quality Objectives, should be used.

It is generally accepted that groundwater plays a role in the ecological Reserve determination if there is a direct hydraulic connection between groundwater and surface water bodies that jointly sustains the aquatic ecosystems. In such situations the often complex role of groundwater (in terms of water level, volume, and water quality), in supporting the ecosystem and human population, has to be ascertained, so that groundwater is not subsequently misallocated. Where aquifers have minimal connection with the aquatic ecosystems, the groundwater component of Reserve would refer to the Basic Human Needs component (25 l/d/person multiplied by the number of people using the groundwater supply in the area).

The broader environmental role of groundwater in supporting important terrestrial ecosystems and hypogean life, particularly in the large semi-arid parts of South Africa, is resource quality objectives.

Once the groundwater component of the RDM has been determined, its role must be sustainable. This is to be achieved through an optimal balancing of competing uses, ensuring that long-term deterioration of the entire groundwater system is minimised. Monitoring and periodic review of allocations is central to this process. The attributes of sustainable development of groundwater resources, such as aquifer physical integrity, deteriorating water quality, etc., will have to be accommodated within the provisions of the National Water Act.

Classification

The classification system prescribed under the National Water Act (NWA) will provide guidelines on how to set appropriate levels of protection for water resources. This chapter outlines guidelines for classification of groundwater resources under the NWA.

The application of this classification system will delineate a groundwater management unit within a significant aquifer resource classed as either Protected, Good, Fair or Severely Modified. These four classes imply different levels of protection and impact acceptable to the stakeholders of the resource. They provide a frame of reference for the implementation of groundwater protection, use and management plans for that groundwater management unit.

This document presents recommendations for a groundwater RDM classification system. It focuses on the role of the groundwater specialist and their technical and scientific input to the process. That role will have to be performed in parallel to surface water specialists and a stakeholder participation process.

The following sections outline guidelines and procedures for groundwater specialists contribute to the Classification of groundwater resources. These follow the generic Classification outline described in the NWRS. For each stage of the generic procedure, the following is described:

- The overall aim of that stage of the procedure.
- The role of the groundwater specialist within that stage.
- Generic principles guiding the implementation of that stage.
- Considerations for groundwater which adapt and apply those principles meaningfully to the Classification of groundwater resources.
- Procedural rules to be followed in the Classification of groundwater.

- Recommended tools to be used in the implementation.
- A summary of the outputs from the procedure.

Where relevant, parallel processes which underpin the validity of the procedure will be highlighted. These may include, for example, stakeholder participation or the characterisation of surface water resources.

A summary of the tasks to be performed by the groundwater specialist can be outlined as follows:

- Delineate area
- Delineate groundwater regions.
- Delineate groundwater response units.
- Delineate areas of common groundwater use.
- Indicate the level of importance of various uses ascribed by the stakeholders.
- Delineate areas of multiple groundwater use.
- Identify conflicting and non-conflicting multiple uses.
- Describe the reference conditions of the response zones.
- Describe the present status of preliminary groundwater management units.
- Indicate the vulnerability of the groundwater response zones with respect to:
    - Ecological dependncy
    - Inherent contamination vulnerability
    - Inherent drought vulnerability
    - Over-exploitation risk
    - Current degree of impact
- Delineate management units based on:
    - Current and future requirements for groundwater use.
    - Vulnerability
    - Common actions necessary to manage groundwater for desired levels of use.
- Describe scenarios of management goals and actions for each management unit and the consequences of assigning likely management Classes for
    - All current groundwater uses.
    - Potential and natural groundwater uses.
    - Land-care management
    - Economic development

Groundwater management units will be defined as areas of the catchment, which requires consistent management actions to maintain the desired level of use and protection of groundwater. Their delineation and classification according to a level of impact acceptable to the stakeholders, will be the final outcome of the Classification process. The groundwater specialist has a key role to play in terms of informing stakeholders and other water resource management decision makers.

Groundwater Interaction with Surface Water Bodies

Understanding groundwater interaction with surface water bodies is prerequisite for determination of groundwater component of the Reserve. However this is a poorly understood area in South Africa at present. Geohydrologsts were familiar with analysing streams solely in order to gain a better understanding of recharge mechanisms. South Africa is no exception to this rule (Vegter, 1997). Similarly, hydrologists are not experienced in determining the groundwater fed component of baseflow to rivers in typical South African settings. However, the scope of interaction between surface water bodies and groundwater is being broadened through a process of the ecological Reserve determination, as it includes analyses of the water exchange between the two, especially the floodplain and stream channel.

A summary of current understanding of groundwater interaction with surface water is outlined. A hydrogeomorphologic approach to quantification of groundwater contribution is developed. The proposed new method has improved the Herold method adopted in the WR90 study. Typical riverine, wetland and coastal groundwater environments of South Africa should also be examined. In addition, issues relating to groundwater-dependence of ecosystems and their ability to adjust to changing conditions are important, which are discussed in a separate report.

Setting of the Reserve

The "Reserve" defined in the National Water Act of 1998 can be interpreted as the quantity and quality of groundwater required:

- to satisfy basic human needs by securing a basic water supply for people who are now or who will, in the foreseeable future, be (1) relying on, (2) taking water from, (3) being supplied by, the relevant water resource; and
- to protect aquatic ecosystems, in order to secure ecologically sustainable development and use of the relevant water resource.

The basic human needs Reserve provides for the minimum living requirements of individuals served by the water resource in question, and includes water for essential uses such as drinking, food preparation and personal hygiene (set, for the time being, at 25 l/d/person). The ecological Reserve is largely reliant upon expert judgement and set at a value so as to ensure that the aquatic ecosystem of the identified area is maintained or improved, depending on the Management Class set. The Reserve (i.e. basic human needs and ecological requirements) is defined as both the quantity and quality of the whole water resource, and will vary depending on the class of the resource. The Minister is required to determine the Reserve for all or part of any significant water resource.

The key steps required for such determination are outlined as follows:

- Conceptualise the aquifer system as part of the catchment;
- Indicate which sections of stream are receiving groundwater fed baseflow;
- Conduct flow simulation for groundwater and surface water interaction;
- Undertake water balance studies;
- Carry out on-going model calibration as more monitoring data are available.

Resource Quality Objectives

RQOs provide goals within the management class. They are set by the Minister during the process of classification of significant water resources. They may be seen as goals to aim for, if the management class represents an improvement on an impacted resource, or thresholds or safety nets which represent the limit of acceptable impact. They may be numeric or descriptive.

RQOs are seen as being particularly important for groundwater as they are not restricted to aquatic ecosystems and may therefore represent the important role of aquifers to the wider environment.

It is proposed that a functional approach should be adopted, considering the functions and importance of groundwater use by humans and the environment. The potential functions of aquifers in the environment could be summarised as providing: sources or sinks for water; sources or sinks for nutrients; habitats. Once the various uses have been identified, objectives should be formulated to safeguard those functions. The objectives should be practically measurable and preferably summarised as key indicators. A range of hydraulic (e.g. groundwater gradients, water table levels), hydrochemical (e.g. total dissolved solids, nitrate) and biotic indicators (e.g. thriving vegetation communities, hypogean fauna) could be selected to indicate that aquifers are effectively fulfilling their important uses. It is envisaged that the functions and indicators should be identified by specialists and the importance of those functions and levels of RQOs (based on the risk of impacting on that function) should be set by informed stakeholders. However the reader must note that more information on RQOs will still come from a separate RQOs project.

Conclusion and Recommendation

The RDM determination may be a rapid, intermediate or comprehensive evaluation. The latter may be achieved through improvement and upgrading of the former into a more comprehensive and accurate

Reserve assessment as more information becomes available. We have been convinced through case studies that a single approach should be used for the determination of the groundwater component of the RDM with confidence levels ranging from rapid to comprehensive.

Although the monitoring is out of scope of the research programme, it is realised that the follow-up monitoring process plays a vital role in verification and improvement of RDM determinations.

Case Studies

The proposed approaches were variably applied in three case studies: (1) the Pienaars River catchment; (2) the Kammanassie area and (3) Mutshindudi River catchment. The case studies showed that the conceptualisation of the aquifer system is a key to successful application of the methodology.

Potential problems tend to stem from the lack of existing long-term observation data sets relating to groundwater quality, piezometric levels, etc. This presented a problem throughout and made it particularly difficult to infer reference conditions from present day conditions at the site.

Related Reports

It is recommended that this report be read together with other related reports, namely "Assessing Terrestrial Groundwater Dependent Ecosystems" by Colvin *et al*. "RDM Case Study: Applying the preliminary method to Classify Groundwater Resources in the Kammanassies-Oudtshorn area" by colvin *et al*., "Case study in Pienaars River" by Van Tonder and Zhang, and "Case study in Mutshindudi River" by Van Tonder *et al*. The case studies indicate that all methods (the intermediate and the comprehensive) should be consistent with each other in terms of hydrogeological approaches.

Acknowledgements

The following individuals, including the steering committee members of the programme, are thanked for their input during and after the numerous workshops and case studies held in the past three years, which has facilitated the production of this technical document.

Rhodes University:

Ms D Louw
Prof D Hughes

University of Zululand:

Prof B Kelbe
Mr BK Rawlins

University of the Orange Free State:

Dr I van der Voort

University of the Western Cape:

Dr R Titus

University of Cape Town:

Dr B Harding

CSIR Environmentek :

Dr R Murray
Mr R Meyer
Ms L van Niekerk
Ms S Taljaard
Dr M Classen
Dr D Roux
Ms L Godfrey
Ms L Fraser
Ms S Clarke
Mr I Saayman
Ms A Silinga
Ms M van der Merwe
Ms E Logie

Water Research Commission:

Mr K Pieterson
Dr G Green
Mr H Maaren

Department of Water Affairs and Forestry:

Mr NJ van Wyk
Mr J L J vd Westhuizen
Dr H van Vliet
Dr H MacKay
Ms M Hinsch
Mr E van Wyk
Mr ZM Dziembowski

Mr WE Bertram
Mr M Swart
Mr R Rose
Ms T Belcher
Mr JM Nel
Mr J Wentzel
Ms. J Baron
Dr J Harris

Parsons & Association:
Mr R Parsons

Geoss:
Mr J Conrad

Ninham Shand:
Mr G Tucker
Mr R Blackhurst

Oryx Environmental:
Mr A Duthie

Overberg Water
Mr J Uys

The authors wish to acknowledge the constructive discussion with the DWAF RDM team on a wide range of issues regarding the Reserve determination. Our thanks are extended to organisers and facilitators at the Pienaars River workshop where we were exposed to various parts of the Reserve determination process through the case study. We also wish to extend our gratitude to the participants of the case study of the Swatkops River Catchment, where the practicality and data availability of proposed methodology was tested.

This version is based on the previous progress report (Version 1.0). The authors are grateful to previous contributors: I van der Voort, J Conrad and WH Chiang.

The Water Research Commission is acknowledged for sponsoring this programme. The programme is fully supported by the regional geohydrological staff of the Department of Water Affairs and Forestry. Their active participation during two workshops held in Pretoria has brought the proposed methodology to a touchstone. Mr. J.M Nel of Geohydrology at the Department of Water Affairs and Forestry is thanked for proofreading Version 1.0 of the document. Ms A Sulaiman of the Groundwater Group (Earth Sciences) at the University of the Western Cape provided editorial support to the current Version 1.1. All contributors are gratefully acknowledged for their consistent support and technical input.

This document represents a draft of the final report, and we sincerely appeal to you for additional contributions and comments toward the production of the final document.

1. Introduction

1.1 Purpose

The purpose of this introduction is to outline the programme objectives and outputs. To support the development of tools required to comprehensively quantify RDM for a groundwater, the Water Research Commission (WRC) and the Department of Water Affairs and Forestry (DWAF) approved a research programme entitled "Groundwater Reserve Determination" in 1999. The programme consists of three individual projects, namely, (1) Classification project K5/1091, (2) Reserve Quantification project K5/1090 and (3) Terrestrial Ecosystem project K5/1092.

1.2 Objectives

The methodology for the determination of the groundwater component of the RDM was targeted to be ready by end of 2001 and, after verification, to be gazetted in January 2004. As the groundwater system operates somewhat differently to surface water, it is clear that an alternative approach to the determination of this component of the RDM will be required.

1.2.1 Objectives of the Classification Project

The overall original aims of the Classification project are to provide guidelines from which the Reserve and utilitzable water can be determined, focussing on:

- A method to delineate geographical boundaries of the groundwater component of Reserve.
- Determination of reference conditions for aquifers.
- Determination of an appropriate classification based on qualitative risk assessment and taking into account importance, sensitivity and economic value.

During the evolution of the project and the formation of the WRC Groundwater RDM programme, the aims of this component have shifted slightly to include a greater emphasis on the application of the generic Classification methodology to groundwater RDM assessment at different levels of confidence. The Classification method provides the framework for resource protection and assessment within which the Reserve and Resource Quality Objectives assessment occurs.

1.2.2 Objectives of the Reserve Quantification Project

The overall original aims of the Reserve Quantification project are to develop a methodology that can be used to determine groundwater component of the Reserve, focussing on:

- A protocol for the allocation of the reserve.
- A coupled GW/SW model.

- Suite of simple conceptual models.

During the consultation with Steering Committee Members the Groundwater Reserve Programme, the original objectives of this component have shifted from the coupled GW/SW model to a more practical approach to address interaction between groundwater and surface water bodies. The adapted methodology provides the framework for determination of groundwater component of the Reserve.

1.2.3 Objectives of the Terrestrial Ecosystem Project

- Determine the groundwater ecological Reserve necessary to sustain critical selected ecosystems.
- Gather good quality hard field data supporting an integrated assessment of groundwater dependency in comprehensive multidisciplinary case studies.
- Assess the applicability of different field techniques.
- Develop further the methodology necessary for a valid determination of the groundwater component of Reserve that can be practically incorporated into ICM.

The accompanying report 'Assessing Vegetation Ecosystem Dependence on Groundwater' presents the progress to date on this project. The original aims have been slightly modified during the course of the project as a result of the project being part of the overall WRC RDM programme. In addition to these aims, the team has contributed to the development of the overall groundwater RDM methodology. We now have a better understanding of the RDM as a legal tool and accept that terrestrial ecological requirements for groundwater will be protected under the Resource Quality Objectives and not the Reserve.

The accompanying report defines a protocol to assess dependency of Terrestrial Groundwater Dependent Ecosystems (TGDEs) and present tools that may be used in South Africa settings. Two field studies have been conducted, one in a primary coastal aquifer and one in a mountainous secondary aquifer.

1.3 Progress

1.3.1 Classification Progress

The Classification system presented provides rules and recommendations for tools to be used in order to:

- Delineate the area
- Delineate Groundwater regions

- Delineate Groundwater response units
- Determine the reference conditions and present status
- Determine the importance and vulnerability of the resource
- Delineate groundwater management units and set the management class

The approach presented can be characterised as:

- Flexible - in requesting the Geohydrologst to select best available tools and defend their application in different hydrogeological settings;
- Transparent - with recorded assumptions and confidence
- Semi-quantitative - in that it relies on effectively combining expert knowledge, stakeholder values and measured aquifer parameters
- Risk based – in balancing management actions against vulnerability and importance
- Functional - in placing the groundwater requirements of users as a priority.

The end result of the application of the methodology presented here will be the delineation of groundwater management units in which RQOs are set and impacting activities managed according to the level of modification acceptable to stakeholders.

An example of Classification is presented in the accompanying volume "Preliminary Classification of Groundwater Resources under the National Water Act: A Worked Example for the Kammanassie – Oudtshoorn area"

It has been essential to align the efforts of the WRC Groundwater RDM Programme with those of other components of the RDM process and we have been involved with the overall RDM revision process as well as directly in contact with other groups such as surface water quality, wetlands and estuaries.

1.3.2 Reserve Quantification Progress

During the consultation with Prof. D Hughes on January 21 of 2000, the team was requested not to pursue the development of the coupled SW/GW model. Instead a more practical approach using spreadsheets was adopted.

Having gone through various consultations with relevant parties, we have accordingly developed the following spreadsheet outputs:

- Software: Groundwater Reserve Quantification (GWRESERVE_Ver1) and its adaptation
- Software: Updated Recharge Programme (Recharge)
- Hydrograph-separation Programme (Baseflow)

It has been essential to liaison with the DWAF staff and improve the software in order to make the software user-friendly for them to apply in the RDM process. A successful workshop was held in Pretoria. The Modified GWRESERVE_Ver1, presented by the team, was well received by the Geohydrology of the DWAF.

2. Background

2.1 Purpose

There is a need to provide the reader with current understanding of groundwater resource protection. The purpose of this chapter is to provide background, principles, and a conceptual framework within which groundwater resource protection and the groundwater component of the Resource Directed Measures in terms of the National Water Act, 1998 can be developed and implemented as part of Integrated Water Resource Management.

2.2 Legislative Background

2.2.1 Role of Groundwater

Groundwater is a renewable and finite natural resource, vital for the life of human, for social and economic development and moreover a valuable component of the ecosystem. Its strategic importance, worldwide, lies in its role as reliable source of drinking water both locally and regionally. Its special characteristics also make it ideally suited for various forms of conjunctive use together with other water sources, and thus achieve a more optimal use of the total resource.

Under the previous government's focus on bulk water supply, groundwater was classified as private water and was only of importance for the farming community and smaller settlements in the drier western parts of the country, where no sustainable surface water sources occur. With the recent policy shift towards development of the whole population, the recognition of impending national water scarcity and the acceptance of the imperative of sustainable development of available water resources, groundwater's role is changing dramatically in South Africa.

While previously groundwater's overall contribution was expressed as 15% of bulk water supply, it is presently recognised that it is contributing between 45-60% to domestic water supply, whereas its contribution to rural water supply, countrywide, could potentially be 90%. The need for conjunctive use and Integrated Water Resource Management is also resulting in renewed groundwater exploration and systems understanding. It is becoming recognised that our hard-rock groundwater systems are making significant contributions to aquatic and terrestrial ecosystems countrywide. Furthermore, new experience shows that yields of these systems could be locally increased by orders of magnitude under favourable fracture conditions and with the appropriate exploration and development investment.

2.2.2 Water Resource Protection

The National Water Act was promulgated in 1998 with the purpose to ensure the optimal and sustainable use of the country's limited water resources for the benefit of its diverse and growing population. In line with international trends, the Act has moved beyond the traditional impact management, including the control of pollution sources (source protection), to a comprehensive and pro-active water resource protection (resource protection). Resource protection is a key objective of the Act and is addressed through Resource Directed Measures. That groundwater is covered by these special measures by means of its definition in the Act as a "significant water resource", is a major step forward from its previous private water status. However, realisation of these policies towards effective groundwater resource protection in South Africa will require continued attention, because of groundwater's past neglect.

Worldwide, little attention had been given to the protection of groundwater resources in the past, mainly because people were unaware of the threats to this hidden resource. Only in the fifties was there a recognition of a major environmental problem due to groundwater's vulnerable nature and accumulating impacts of human development. In the sixties the conceptual approach to groundwater resource protection, based on monitoring, mapping, modelling and remediation technology was developed. Sustainable groundwater development and use and environmentally sound protection of groundwater became important elements of national water planning, policy and strategy in the course of the eighties. Integration of land use activities in the concept of groundwater protection policy, public involvement in groundwater protection issues, social and health aspects all became part of groundwater protection and quality conservation policies in different countries. A holistic concept for water resource policy and management as emphasised at the International Conference on Water and the Environment in Dublin (1992), significantly influenced the approach to the development, use and protection of water resources in the nineties. The holistic approach to groundwater protection reflects the social, economic and ecological value of groundwater, considers the closer connection between groundwater, surface water and soilwater and gives the same attention to both quantitative and qualitative aspects. It deals simultaneously with sustainable economic development, maintenance of ecosystem integrity and environmentally sound protection of groundwater resources.

The National Water Act places emphasis on protection of water resources for their sustainable utilisation. For purpose of groundwater protection, first defence would be the General Authorisations. The RDM forms core of the protective measures, which consists of three important aspects, namely resource classification, Reserve determination and resource quality objectives (MacKay, 1999). This guideline will focus on the Reserve determination.

2.3 RDM for Groundwater Resources

2.3.1 Concept of the RDM

For purpose of groundwater protection, all three mechanisms of the RDM, namely Classification, Setting of the Reserve and Resource Quality Objectives, should be used. Every RDM measure, i.e. the Reserve, ecological and basic human needs, Classification and Resource Quality Objectives, has its place in resource protection and should be used as such for groundwater protection. A proposed use of these measures for groundwater protection, individually or in combination, is illustrated in Figure 2.1.

Figure 2.1: Resource Directed Measures for Groundwater Protection.

- Ecological Reserve: A groundwater contribution is determined, where there is a linked aquatic ecosystem that requires protection.

- Basic Human Needs Reserve: A Reserve is determined where people take water from or are being supplied from the groundwater resource. This process is not dependent on whether the groundwater contributes to an Ecological Reserve.

- Classification: Classification should be used in combination with the determination of both Reserve components, as well as for the protection of groundwater resources where neither of the Reserve components is relevant.

- Reserve Quality Objectives: These should be set for each of the three above measures to express the management requirements for the groundwater resource in more specific and executable terms. For a combination of measures (higher level objectives), Resource Quality Objectives should be prioritised and combined into one RWQ.

The above has a number of important implications:

1) There can be a Reserve for groundwater per se and not only for surface water, i.e. where a groundwater resource requires a Basic Human Needs Reserve.

2) Because of groundwater's strategic importance and world-wide first choice for domestic water supply, one could see the Basic Human Needs Reserve component implemented wherever groundwater is playing, or could play in future, a sole source role. According to a definition utilised by the USEPA and taken over in the South African aquifer classification system (Parsons, 1995), a Sole Source Aquifer System is an aquifer which is used to supply 50% or more of domestic water for a given area and for which there are no reasonably available alternative sources should the aquifer be impacted upon or depleted.

3) Ecological Reserve is intended to address aquatic ecosystems. The role of groundwater in supporting important terrestrial ecosystems and hypogean life, particularly in the large semi-arid parts of South Africa, is not accommodated in the Reserve concept. The full ecosystem functioning of groundwater can be protected under the resource quality objectives.

2.3.2 Complications of South African aquifers

Before we consider how the identified groundwater in a delineated water management area is to be apportioned between the Reserve and allocatable component, we must briefly take into account the often complicated hydraulic characteristics of aquifers in South Africa.

According to Vegter (1995), there are five major types of aquifer systems that can be recognised in the country, namely:

Primary aquifers;

Karoo aquifers;

Fractured sandstone aquifers;

Fractured & cavernous dolomitic aquifers;

Other weathered & fractured basement aquifers.

Fractured-rock conditions are believed to apply to over 90% of South Africa. Most aquifers in South Africa are, to a degree, both porous and highly fractured (Figure 2.2). Two types of porosity coexist in such aquifers, each with distinct flow characteristics.

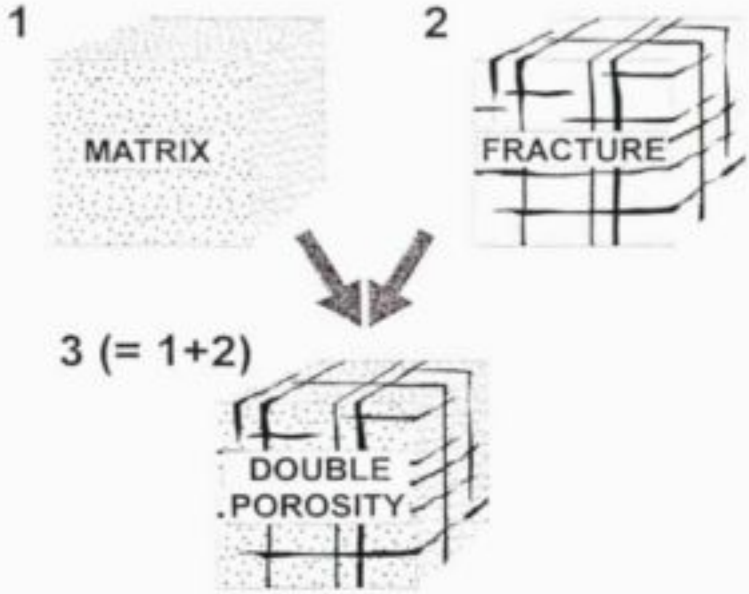

Figure 2.2: Different media 1. Matrix; 2. Fracture network and 3. Double porosity.

Fractured aquifers are typically characterised by their low storativity, high anisotropy and high heterogeneity. This makes them less predictable than isotropic, homogeneous primary aquifers. Their nature will make delineating groundwater response units and management units more difficult as lithological boundaries alone may not always be used. Also, it is more difficult to predict where groundwater fed baseflow to rivers occurs.

2.3.3 Definition of the Reserve

According to the National Water Act of 1998, "Reserve", in terms of geohydrology, means the quantity and quality of groundwater required:

- to satisfy basic human needs by securing a basic water supply for people who are now or who will, in the foreseeable future, be (1) relying on, (2) taking water from, (3) being supplied by, the relevant water resource; and
- to protect aquatic ecosystems, in order to secure ecologically sustainable development and use of the relevant water resource.

The former provides for the minimum living requirements of individuals served by the water resource in question and includes water for essential uses, such as drinking, food preparation and personal hygiene (set, for the time being, at 25 l/d/person). The latter is largely reliant upon expert judgement and set at a value so as to ensure that the natural ecology of the identified area is maintained or improved, depending on the Management Class set. The Reserve (i.e. basic human needs and ecological) should be defined as both a quantity and quality of the whole water resource, and will vary depending on the class of the resource. The Minister is required to determine the Reserve for all or part of any significant water resource.

The biggest difficulty still surrounds the conceptual issues of the Reserve and determination-related implications of the relatively simple definition put forward in the new Act. The following are some points for discussion:

- The volume of accessible water that satisfies basic human needs as well as ecological requirements.
- Where and how to express the Reserve.
- The Reserve is spatially referenced. It is necessary to define it in terms of buffer zones or areas.
- What about temporal variability?
- Can the groundwater resource be considered as being part of the ecological system? Is aquifer integrity also a part of, or related to, the ecological system?
- Minimisation of any negative impacts.
- How to expand and elaborate on the current concept of the Reserve.

Based on the above, challenges of the Reserve concept for groundwater are listed as follows:

1) Aquifer boundaries are different from catchment boundaries;
2) 3D nature of catchment;
3) Area-based protection requirement;
4) Protection of aquatic ecosystem;
5) Aquifer itself as aquatic ecosystem;
6) Sustainable use of groundwater;
7) Local impacts and spatial variability;
8) Role of storage and slow response of system.

2.3.4 Groundwater-vegetation interaction

An overview of groundwater-vegetation interactions is given in a separate report entitled "Assessing Vegetation Ecosystem Dependence on Groundwater". The new integrated approach to water resource management brought in by the Water Law Principles and Water Act (Act No 36 of 1998) requires that vegetation use of groundwater be considered. Groundwater-vegetation interactions occur close to or at the surface of the earth and therefore are closely linked to the other surface water based components of the Reserve. These close links emphasise the need for close integration of the methodologies involved in Reserve determination to ensure a consistent approach and to explicitly account for the interdependencies (MacKay, 1998b).

Some examples in South Africa are discussed in more detail in the report entitled "Assessing Vegetation Ecosystems Dependence on Groundwater" by Colvin *et al.* Baseflow-dependent ecosystems, especially in semi-arid to arid areas, are important for biodiversity, offering refuge and ideal habitats for a variety of organisms (Milton 1990, Naiman *et al.* 1993; Morrison *et al.* 1994). A good South African example is the Sabie-Sand River system in the Kruger National Park where the riparian ecosystems play key roles in the maintaining the biodiversity and functioning of the adjoining terrestrial ecosystems (Davies *et al.* 1993, Birkhead *et al.* 1997, Jewitt *et al.* 1998). Other examples are river systems with strongly seasonal flows such as the Letaba River and some tributaries of the Limpopo River system or the ephemeral river systems in the southern Kalahari (e.g. the Molopo River).

There is very little information on these groundwater-dependent systems and studies are urgently needed to obtain more detailed information, regarding the nature of the water resources being used by the vegetation and the nature and extent of groundwater dependence.

2.3.5 Groundwater resource quality objectives

RQOs provide goals within the management class. They are set by the Minister during the process of classification of significant water resources. They may be seen as goals to aim for, if the management class represents an improvement on an impacted resource, or thresholds or safety nets which represent the limit of acceptable impact. They may be numeric or descriptive.

RQOs are seen as being particularly important for groundwater as they are not restricted to aquatic ecosystems and may therefore represent the important role of aquifers to the wider environment. Guidelines to set comprehensive RQOs are not specifically included in the Terms of Reference of this programme, but a project has now been initiated to provide these. The results of this project will be fully integrated with the rest of the Groundwater Reserve programme.

It is proposed that a functional approach should be adopted, considering all important direct and indirect uses of groundwater. The potential functions of aquifers in the environment could be summarised as providing: sources or sinks for water; sources or sinks for nutrients; habitats. Once the various uses have been identified, objectives should be formulated to safeguard those functions. The objectives should be practically measurable and preferably summarised as key indicators. A range of hydraulic (e.g. groundwater gradients, water table levels), hydrochemical (e.g. total dissolved solids, nitrate) and biotic indicators (e.g. thriving vegetation communities, hypogean fauna) could be selected to indicate that aquifers are effectively fulfilling their important functions in the environment. It is envisaged that the functions and indicators should be identified by specialists and the importance of those functions and levels of RQOs (based on the risk of impacting on that function) should be set by informed stakeholders.

2.3.6 *Implementation of the RDM*

Officially, from October 1st, 1999, a preliminary Reserve evaluation of a management area should be determined if a license application, for water allocation, is processed. If water resources in the delineated area are not stressed, relatively low confidence rapid or intermediate RDM assessments may be done. Where resources are under competing stress, a higher confidence comprehensive assessment should be conducted including significant field study and stakeholder consultation. A rapid estimate may be improved and upgraded into a more comprehensive and accurate Reserve assessment, as more information becomes available.

2.4 Framework for the RDM Assessment

It is the fundamental fact that the RDM determination is an integrated process. Groundwater must be viewed as an important part of the hydrologic cycle. Typical scenarios of groundwater interaction with surface water bodies should be depicted and investigated. The idea of such typical scenarios was put forward by Braune and Dziembowski (1997) and adopted by Parsons (1999) in terms of the geohydrological regions.

Sustainable development is traditionally defined as "development that meets the needs of the present without compromising the ability of future generations to meet their own needs" (WCED, 1987). Therefore, when applied to the context of the Groundwater component of Reserve of South Africa, management of the total resource (including the allocatable portion) should be performed in a manner that ensures depletion (of quality and quantity) does not occur over the long-term.

The recharge of an aquifer, over time, is reliant upon two major factors:

1) Recharge - i.e. quantity of water filtering through to aquifer; and

2) Outputs - e.g. pumping water from boreholes for human use.

As recharge is predominantly reliant upon meteorological and surface conditions, its variation can be seen to be part of an inherently 'natural' system and normally beyond human control. However, human impact, on the outputs from a groundwater resource, can be much more significant.

To prevent long-term degradation of the groundwater resource, it seems logical that overall abstraction within the area should not exceed the average annual recharge in a business-as-usual scenario and practices that are likely to deplete the overall resource should be discouraged. Additionally, the storage issue, related to the dual-porosity of much of South Africa's aquifers, should be accounted for, so that potential overallocation can be avoided.

The total sustainably available groundwater in any given area, once quantified and decided upon, can be divided into two potential or actual usage groups: the 'Reserve' (already outlined); and the allocatable component. The division of the resource is decided upon by virtue of the identification of the overall Groundwater component of Reserve which, in itself, is a component of the identified and agreed-upon Reserve for the delineated water management area (i.e. once the Reserve is identified, the role of groundwater needs to be ascertained). The remaining groundwater, within the planning unit, can be considered as available for allocation. Simply put, subtracting the groundwater component of the Reserve from the total, sustainably abstractable, groundwater for a given area may leave a remainder, the allocatable component.

As previously outlined, the Reserve has two components (ecological and basic human needs). Therefore, the groundwater resource has been divided into 3 distinct use-groups (Table 2.1): basic human needs Reserve (B); Ecological Reserve (E); and the remaining Allocatable Component (A).

There is a range of possible groundwater availability scenarios for any water management area. Moreover, the environmental and geographic status of any individual area is likely to vary spatially to a considerable degree. As the considered importance and significance of the 3 aforementioned groundwater use-groups rely somewhat upon these factors, it can be seen that the balance and interplay of the classes is likely to vary accordingly, depending on the "local" situation.

Using a box to represent the identified total, sustainably obtainable groundwater resource in a delineated area, we can envisage this total being comprised of the above 3 use-groups in varying amounts, depending on the local situation. Figure 2.3 illustrates a matrix of possible extreme groundwater situations.

Table 2.1: Brief description of 3 basic use-groups of ground water, according to availability and potential usage.

Name (tag)	Description
Ecological Reserve (E)	Agreed amount of water required locally and/or downstream to maintain/improve local ecology.
Basic Human Needs (B)	Agreed minimum amount of water guaranteed as a right for every South African citizen, to suit basic human needs, such as cooking and cleaning.
Allocatable (A)	Remaining quantity of water, once Reserve has been determined and subtracted from the quantified total amount of water economically available.

As we move from left to right, along the x axis of Figure 2.3, the allocatable component becomes

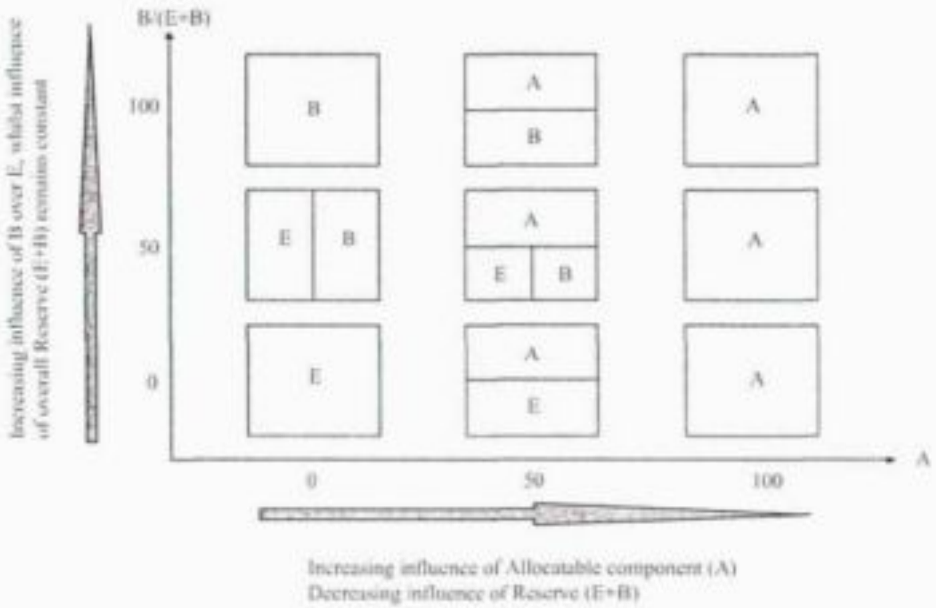

Figure 2.3: Matrix for visualising theoretical combinations of groundwater use groups due to decisions made regarding allocation and Reserve determination.

increasingly significant, as a proportion of the overall 'usable' groundwater resource (and hence, the Reserve component becomes increasingly insignificant, volumetrically). If we move upwards along the y axis, the total Reserve remains constant, but the relative significance of basic human needs over ecological requirements increases. Combining the two variables provides a matrix of theoretical scenarios, covering the wide range of possible local groundwater situations in a water management area.

Once a figure for the total Reserve of a delineated area is set (composed of basic human and ecological needs), the remainder (adhering to the sustainability criteria, outlined above) may be allocated for other uses.

Decisions, concerning the division of the resource, are ultimately likely to be made by a local governing authority, with reference to the expert judgement of the panel whose work contributed to the decided-upon Reserve and the Minister, whose task it is to *set* the Reserve. In areas under water stress, it can be envisaged that local authorities may have to carefully balance the needs of the local ecology with the future economic and social development of the water management area. However, "squeezing out" the ecological component, by moving either too far towards allocation (left to right along the x axis), or allowing human populations to put too much pressure on the finite resource (moving upwards on the y axis), is an undesirable and unsustainable way forward and, therefore, should be avoided. A well-planned resource in an area of conflicting needs should optimally balance all interests.

Finally, determination of groundwater component of the RDM may always surfer from a certain degree of uncertainty due to complicated aquifer systems involved. Therefore any determined results should be treated under the stochastic framework.

3. Classification

3.1 Introduction

The classification system prescribed under the National Water Act (NWA) will provide guidelines on how to set appropriate levels of protection for water resources. This chapter outlines guidelines and discussion for classification of *groundwater* resources under the NWA.

The application of this classification system will delineate a groundwater management unit within a significant aquifer resource classed as either Protected, Good, Fair or Severely Modified. These four classes imply different levels of resource protection and impact acceptable to stakeholders. They provide a frame of reference for the implementation of groundwater protection, use and management plans for that groundwater management unit.

Other classification systems exist, for example classes of water suitability for different uses (DWAF, DOH, WRC, 1998), classes of aquifers based on their productivity and the dependency of human users (Parsons and Conrad, 1995), and groundwater contaminant vulnerability (Reynders and Lynch, 1993; Parsons and Conrad, 1995). The classification system presented here is defined by the RDM process and is compatible with the RDM classification of other water components such as estuaries, wetlands and rivers. It incorporates other technical classification and assessment systems where they are appropriate, such as the modified DRASTIC aquifer vulnerability classification.

Chapter 3 of the NWA sets out legal mechanisms to protect water resources. The Resource Directed Measures (RDMs) include Classification and setting Resource Quality Objectives (RQOs) as well as the Reserve. Chapter 3 of the NWA also describes Source Directed Controls (SDCs) which aim to minimise the impact of certain polluting activities.

The *Classification System* provides a framework for the application of these measures. It is the first stage in the protection process. The NWA states that the classification system should provide guidelines and procedures for determining different classes of water resources. For each class of water resource there should then be procedures to determine the Reserve, management procedures to satisfy the water quality requirements of water users (as far as possible) and regulations to protect the resource from the impacts of land-based and in-stream activities. The classification system therefore provides a set of nationally consistent rules to guide decision making about water resources.

DWAF has developed a risk-based approach to classification which attempts to balance the need to protect with the importance of the resource. The decision on the optimal balance is in the hands of the

Minister in consultation with representative stakeholders such as the CMA. The different classes assigned to water resources represent different levels of acceptable risk of modification from natural conditions.

It is necessary to assess the present status of a resource by considering the degree of modification from natural conditions, and consequently the degree of risk of irreversible damage to the resource. Future management classes are then set as targets for the protection and management of a resource. Once this process has been completed, the Reserve and RQOs can be set according to the desired management class. Certain uses require a low degree of modification, typically environmental uses and Basic Human Needs. If these uses are deemed important by stakeholders, a highly protected class may be assigned.

3.2 The establishment of a Classification system

In 1999, DWAF outlined the generic Seven Step Methodology for implementation of the RDM. This is actually the scientific and technical component of a Ten Step Method (DWAF, 1999). The additional three steps are part of the longer term management of the resource. This generic methodology has been revised since 1999 and later publications on determination of the ecological Reserve for surface water resources (DWAF, 2002a) and the National Water Resources Strategy (NWRS) (DWAF, 2001) represent the revised approach to RDM implementation. Many of the key principles presented in the original 15 volumes of 1999 are still valid.

The classification system for water resources will be established, after public consultation, by means of a Regulation in terms of section 12 of the Act. Until this regulation, all classification will be termed preliminary. DWAF aims to Gazette the methodology for RDM implementation in 2004.

Actual determination of the class of a water resource, and determination of the Reserve, will be the subject of Government Notices, after public consultation, in terms of Sections 13 and 16 of the NWA (DWAF, 2001).

3.3 Aims of this chapter

This chapter presents recommendations for a groundwater RDM classification system. It focuses on the role of the groundwater specialist and their technical and scientific input to the process. That role will have to be performed in parallel to surface water specialists and a stakeholder participation process.

This chapter aims to present rules for groundwater classification in order to help hydrogeologists to apply sound, defensible protocols and tools to classify groundwater resources. It aims to align rules for groundwater classification with those being developed generically and for surface water by DWAF. Appendix A, accompanying this document, illustrates a case study where the proposed approach is applied. It shows the key GIS based outputs of the process and discusses data issues found to be relevant during the application.

The methods and guidelines proposed are intended to:

- Be legally and scientifically defensible;
- Be simple and operable;
- Contain a limited number of classes;
- Use similar concepts and terminology as other the water resource components

  (estuaries, rivers and wetlands).

The guidelines presented in this document will need to be widely reviewed and approved prior to the finalisation of the methodologies for all water resources in 2004. Further work funded by the WRC on guidelines to set RQOs should be incorporated into the final draft Classification approach for groundwater. This is scheduled for completion in September 2002.

3.4 A legally defensible classification system

In order to prescribe a legally defensible classification system for groundwater, we need to be clear about how the NWA describes the classification system. Sections from the National Water Act (1998) are quoted in italics below, and their implication for the groundwater classification method discussed.

The protection of water resources is fundamentally related to their use, development, conservation, management and control.

Water resources, and therefore aquifers, need to be protected to maintain their useful functioning within the catchment. The level of protection and degree of impact acceptable, needs to be viewed in terms of the required and accepted use and management of the aquifer.

Parts 1, 2 and 3 of Chapter 3 lay down a series of measures [RDM] which are together intended to ensure the comprehensive protection of all water resources.

The RDM should be implemented as a whole (classification, RQOs and the Reserve) in order to realise the protection of water resources. Although the current licensing procedure requires that the Reserve alone should be determined before a license is granted, DWAF and CMAs should attempt to roll-out the RDM as an integrated set of measures.

These measures [RDM] are to be developed <u>progressively</u> within the contexts of the national water resource strategy and the catchment management strategies.

We will not be able to set and achieve the class and RQOs for groundwater in short or easy steps. We will need to move progressively towards the goals agreed upon by stakeholders. The requirements of the RDM and resource management actions required for their implementation must be included in the NWRS and CMSs.

Part 1 [Chapter 3] provides for the <u>first stage</u> in the protection process, which is the development by the Minister of a system to classify the nation's water resources.

The classification system provides the framework for groundwater protection. This framework needs to be established before reliable RQOs and the Reserve can be set. The class of the resource sets the context for the levels of protection to be realised through the RQOs and the Reserve.

The system provides <u>guidelines and procedures</u> for determining different classes of water resources.

The classification system itself provides guidelines on setting the class for groundwater resources within CMAs. These guidelines should comprise rules for determining the level of protection required, recommended best practice in applying the guidelines and available tools. These should be applied country-wide, in a progressive and prioritised manner, in order to classify groundwater resources. It is expected that once the classification system is agreed upon, it will take up to 10 years to classify the nation's groundwater resources.

The system for classifying water resources may -

- ***(a)*** ***establish guidelines and procedures for determining different classes of water resources;***
- ***(b)*** ***in respect of each class of water resource -***
  - ***(i) establish procedures for determining the Reserve;***
  - ***(ii) establish procedures which are designed to satisfy the water quality requirements of water users as far as is reasonably possible, without significantly altering the natural water quality characteristics of the resource;***

(iii) set out water uses for instream or land-based activities which activities must be regulated or prohibited in order to protect the water resource; and

(c) provide for such other matters relating to the protection, use, development, conservation, management and control of water resources, as the Minister considers necessary.

Procedures to determine the quantity of the groundwater component of the Reserve are addressed in chapter 5 of this document. Procedures to satisfy the water quality requirements of water users relate to the protection of aquifers from pollution. This must be practically possible and therefore take into account the natural or reference condition for water quality in the area. In addition, it needs to be balanced against the need to use and develop our resources. The NWA requires that the water quality required by users should be maintained, not the pristine quality of the aquifer. Therefore a level of acceptable impact on the resource in terms of water quality should be agreed upon. [More detail on water quality procedures will be given in the accompanying RQO guidelines].

Certain activities which are most probable to cause pollution to an aquifer will need to be regulated in vulnerable areas. It will be necessary to understand the vulnerability of significant groundwater resources to pollution and drought in order to apply focussed, effective protection measures.

The Minister is required to use the classification to determine the reserve and resource quality objectives of all or part of water resources considered to be significant. The purpose of the resource quality objectives is to establish clear goals relating to the quality of the relevant water resources. In determining resource quality objectives a balance must be sought between the need to protect and sustain water resources on the one hand, and the need to develop and use them on the other.

Again, the legal emphasis is on protection *for* use and not protection *at the cost of* use.

Before determining a class or the resource quality objectives in terms of subsection (1), the Minister must in respect of each water resource -

(a) publish a notice in the Gazette -

(i) setting out -

(aa) the proposed class;

(bb) the proposed resource quality objectives;

(cc) the geographical area in respect of which the objectives will apply;

(dd) the dates from which specific objectives will apply; and

(ee) the requirements for complying with the objectives; and

(ii) inviting written comments to be submitted on the proposed class or proposed resource quality objectives (as the case may be), specifying an address to which

and a date before which the comments are to be submitted, which date may not be earlier than 60 days after publication of the notice;

(b) consider what further steps, if any, are appropriate to bring the contents of the notice to the attention of interested persons, and take those steps which the Minister considers to be appropriate; and

(c) consider all comments received on or before the date specified.

Setting the Class, the Reserve and RQOs is a participative process that must take into account comments of stakeholders. Scientists may determine various RDM scenarios, but the RDMs are set by the Minister, in consultation with stakeholders. The final setting of the class should therefore represent the needs of stakeholders in the catchment. This will require effective communication from groundwater specialists to decision makers and the public about the occurrence, importance and vulnerability of groundwater. For stakeholders to participate meaningfully in the process, they will need to understand the implications of setting different classes for groundwater. Hydrogeologists have a key role to play in informing stakeholder of the consequences of the decisions in terms of protection and use of groundwater.

The Minister must, subject to subsection (4), by notice in the Gazette, determine for all or part of every significant water resource -

- ***(a) a class in accordance with the prescribed classification system; and***
- ***(b) resource quality objectives based on the class.***

A notice must state the geographical area in respect of which the resource quality objectives will apply, the requirements for achieving the objectives, and the dates from which the objectives will apply.

The class itself represents a level of protection or impact acceptable to stakeholders. The RQOs give effect to the class by prescribing certain water resource goals to be achieved and activities to be controlled. The outcome of classification is therefore a relatively simple term Protected, Good, Fair or Severely Modified for a designated area. However the process for classification is more complex and needs to relate intricately to the RQOs and Reserve, as the final decision on a class will depend on the understanding of the consequences of the RQOs and Reserve necessary to achieve it.

The Reserve refers to both the quantity and quality of the water in the resource, and will vary depending on the class of the resource.

As is the case for the RQOs, the level of protection set for the Reserve will depend on the class set. Conversely, the Class set will depend on an understanding of the implications for Reserve protection. A Reserve determination carried out without reference to the Class of the resource will have questionable legal validity.

3.5 The generic process - concepts and terminology

Guidance on the broad principles to be adopted by the classification method is found in preliminary inputs to the draft NWRS (DWAF, 2001) and in the Volume 8 of the RDM policy implementation series (DWAF, 1999). Some of the principles outlined in the 1999 document have been superseded by the draft NWRS.

Input to the draft NWRS states that:

> *"A water resource classification system is being developed which will provide a consistent national framework within which water resources can be grouped into broad classes, each class representing a different level of protection and, consequently, a different level of utilization. The system will provide specifications against which to make management decisions about the nature and extent of permissible, sustainable resource use."*
>
> *"Although the management class of a resource will focus strongly on the requirements for ecosystem protection (which may be described as an ecological class), it must also take account of the water quality requirements of water users, insofar as it is possible to satisfy user requirements "without significantly altering the natural water quality characteristics of the resource" (section 12(2)(b)(ii). The use of resources to supply water for basic human needs or for irrigating sensitive crops, or for recreation may, for instance, require modifications to the ecological class specifications."*

3.5.1 Definitions of the classes

"Four ***management classes*** *are proposed:*

Protected: *A Protected resource may be one in which:*

- *Human activity has caused no or minimal changes to biological communities (animals and plants), to the hydrological characteristics, or to the bed, banks and channel of the resource.*
- *Chemical concentrations are not significantly different from background concentration levels or ranges for naturally occurring substances; and*
- *Concentration levels of artificial substances do not exceed the detection limits of advanced analytical methodologies.*

All of the above conditions must be satisfied. Criteria for classification as Protected will include: national or international heritage site or areas; biodiversity; the Ramsar Wetlands Convention; economic (tourism, medicinal *plants) and social/cultural considerations; and areas designated as Protected under any other legislation."*

The Protected class is a reference condition. Resources in other classes will be defined in terms of the degree of deviation from conditions of no or minimal impact.
Good: *In which the condition of the resource is slightly to moderately altered from the Protected, reference conditions.*
Fair: *In which the resource has been significantly changed form reference conditions."*

"Water resources will, as far as possible, be managed to maintain them in their present ecological condition (that is, within the boundaries of their ecological class). However, in some cases there may be pressing social and economic reasons to permit short-term uses which will cause limited degradation of resource condition, and these will be considered on their individual merits."

"Some resources are already in a condition which may be described as Poor (that is, worse than Fair). In these cases the management class will be set as (at least) Fair, and management efforts will aim to rehabilitate the resources to an improved condition."

"In addition, some water resources have been so severely and permanently physically modified that rehabilitation to anything approaching a natural ecosystem would be impossible or prohibitively expensive. Such resources, or parts of resources – rivers which have been canalised through urban areas, or for flood protection, for example – may be classified as ***Severely Modified****. The classification system will provide for the development of resource quality objectives for Severely Modified resources but, as they cannot be regarded as functional ecosystems, the procedures will not involve the determination of an ecological Reserve."*

"The classification system will apply to all surface water resources in South Africa, but it will be sufficiently flexible to accommodate the different characteristics of rivers, wetlands, impoundnents and estuaries. ***Groundwater*** *resources, which are the only available sources of water in many parts of the country, are vulnerable to pollution from land-based activities and practically impossible to rehabilitate once they are polluted. Whilst it will be generically similar to the classification system for surface water, the groundwater system will have its own unique features."*

"The characteristics – quantitative or descriptive – which will be used to classify surface water resources will include:-
Chemical and physico-chemical: *salt concentration; pH; fluoride; nutrient concentrations; dissolved oxygen; temperature; toxic substances; substances identified from an inventory of point and diffuse sources of pollution.*
Biological: *composition and abundance of aquatic flora and benthic invertebrate fauna; composition, abundance and age structure of fish fauna.*
Hydro-morphological: *hydrological regime (quantity and dynamics of water flow, and connection to groundwater); variations in water depths and widths; structure and substrate of river channel; structure or riparian zone."*

"For some resources some characteristics may need to be specified more strictly than the range of values applicable to its management class. For instance, particular uses of a resource which is classified Fair may require those characteristics which relates to eutrophication (excessive growth of algae) to be specified in the range appropriate to the Good class. Similarly, some resources may require specifications for characteristics additional to the standard set."

3.5.2 The generic classification process

Inputs to the draft NWRS outline a proposed process for RDM determinations as follows:-

- Define the geographic extent of the water resource.
- Select the appropriate level of determination.
- Determine the eco-regional type (or types) in the study area, and select survey sites.
- Determine reference conditions, and assess present state, importance and sensitivity.
- Set the management class, determine the Reserve and set RQOs.
- Design and implement a resource-monitoring programme.

This document presents guidelines for the implementation of this generic process for groundwater. Sections 3.9 to 3.15 discuss the key points of the process in terms of the:

- Generic principles currently accepted;
- Special considerations to be made when implementing these generic principles for groundwater;
- A summary of the rules for applying the principles to groundwater classification;
- Recommended tools to be used in applying these principles;
- A summary of the outcomes from that step in the process.

3.5.3 Generic levels of classification

Four levels of determination are proposed:

Desk Top:	Very low confidence. Used only for (the majority of) Reserve determination in national water balance scenarios (WSAM).
Rapid:	Low confidence. Essentially a Desk Top determination plus a cursory field assessment of present ecological state. Used for individual licence applications with low impacts, unstressed catchments of low ecological importance and sensitivity.

Intermediate: Medium confidence. Requires field studies by specialist. Used for individual licence applications in relatively unstressed catchments.

Comprehensive: Relatively high confidence. Requires extensive field studies and data collection by specialists. Used for all compulsory licensing exercises, and also for individual licence application which have large impacts in any catchment, and which have small or large impacts in ecologically important or sensitive catchments.

To ensure that groundwater Classification is aligned to the other components, the principles of the current generic methodology have been adhered to and adapted where necessary.

3.6 Scientific validity

The most frequently recommended tool to be used in Classifying groundwater resources is Expert Knowledge. This means that hydrogeologists with the most expertise and recognised understanding of the local systems should be a key part of the process. Subjective and qualitative descriptions and assessments made by those with the best working knowledge of an area, are thought to be more valuable to the Classification process than automated judgements based on dubious data.

The Classification process needs to be scientifically defensible, and hence repeatable. With limited groundwater expertise and databases of variable or unknown quality, it will be important to keep a record of decision making, which outlines all the assumptions and levels of confidence in decisions made by experts. The approach presented aims to keep the elements that are required to inform the Classification decision separate for as long as possible. It avoids lumping intermediate outputs of the process together and assigning a value. This can be misleading and imply a false confidence in the quantified understanding of the issues. By keeping characteristics separate, subjective decisions remain transparent and open for review.

Each classification process should incorporate peer preview and review of the work, including the outputs, assumptions and confidence. Implementation should also be reviewed by the National DWAF RDM office to ensure continuity and to ensure that the principles of the methodology are being adhered to.

Generic guidance has been given on the processes to determine low, medium and high confidence Classifications. It is recommended that following a Classification process, the confidence be reassigned to take into account the increased understanding. In other words, a Classification team or specialist may work in an area for one year gathering new field data, but at the end of the process understand that some critical areas have not been given due attention. In that case the level may drop to an Intermediate.

The classification system for groundwater resources needs to simultaneously take into account groundwater use, importance and vulnerability. Attributes which characterise groundwater systems may be biophysical, economic, social and ethical. Reconciling all these attributes in one system requires subjective, expert, adjudicated decision making. To improve the validity of the process, the following characteristics of the Classification system should be adhered to:

- Flexible - in requesting the hydrogeologist to select best available tools and defend their application in different hydrogeological settings;
- Transparent - with recorded assumptions and confidence
- Semi-quantitative - in that it relies on effectively combining expert knowledge, stakeholder values and measured aquifer parameters
- Risk based – in balancing management actions against vulnerability and importance
- Functional - in placing the groundwater requirements of users as a priority.

3.7 A simple and operable approach

Scientists, decision makers and stakeholders are often at odds in their requirements for systematic evaluation of natural resources. Decision makers need broad lumped values, such as annual volumes per aquifer, in order to plan water allocations. Stakeholders need high confidence in the protection of their smaller scale interests. Scientists often find it difficult to make predictions and assess impacts as they begin to unravel the complexity, heterogeneity and unpredictability of natural systems. However, these needs and conflicting viewpoints must find common ground in the Classification system.

In the words of Hippocrates, *'Life is short, science is lengthy, opportunity is elusive, experience is dangerous, and judgement is difficult.'* We need to make sound decisions based on the best possible scientific information and taking into account the views of stakeholders. These guidelines do not present complex detail on the selection of tools and datasets in different areas of the country at different levels of confidence. This guidance would be rapidly outdated. Instead, the specialist is informed of possible options and asked to record and defend their decisions. The groundwater specialist should provide justification of tools and datasets used with respect to:

- availability
- affordability

- appropriate spatial and temporal scales
- appropriate confidence and assumptions in the particular hydrogeological setting.

3.8 Guidelines and procedures to classify groundwater resources

The following sections outline guidelines and procedures for groundwater specialists contributing to the Classification of groundwater resources. These follow the generic Classification outline described in the NWRS.

For each stage of the generic procedure, the following is described:

- The overall aim of that stage of the procedure.
- The role of the groundwater specialist within that stage.
- Generic principles guiding the implementation of that stage.
- Considerations for groundwater which adapt and apply those principles meaningfully to the Classification of groundwater resources.
- Procedural rules to be followed in the Classification of groundwater.
- Recommended tools to be used in the implementation.
- A summary of the outputs from the procedure.

Where relevant, parallel processes which underpin the validity of the procedure will be highlighted. These may include, for example, stakeholder participation or the characterisation of surface water resources.

A summary of the tasks to be performed by the groundwater specialist is shown in Figure 3.1 and outlined below as follows:

Delineate area.

Delineate groundwater regions.

Delineate groundwater response zones.

Describe the reference conditions of the response zones.

Delineate areas of common groundwater use.

Delineate areas of multiple groundwater use.

Describe the present status of preliminary groundwater management units.

Indicate the level of importance of various uses ascribed by the stakeholders.

Indicate the vulnerability of the groundwater response units with respect to:

- Ecological dependency
- Inherent contamination vulnerability
- Inherent drought vulnerability
- Over-exploitation risk
- Current degree of impact

Delineate management units based on:

- Current and future requirements for groundwater use.
- Vulnerability
- Common actions necessary to manage groundwater for desired levels of use.

Describe scenarios of management goals and actions for each management unit and the consequences of assigning likely management Classes for

- All current groundwater uses.
- Potential and natural groundwater uses.
- Land-care management
- Economic development

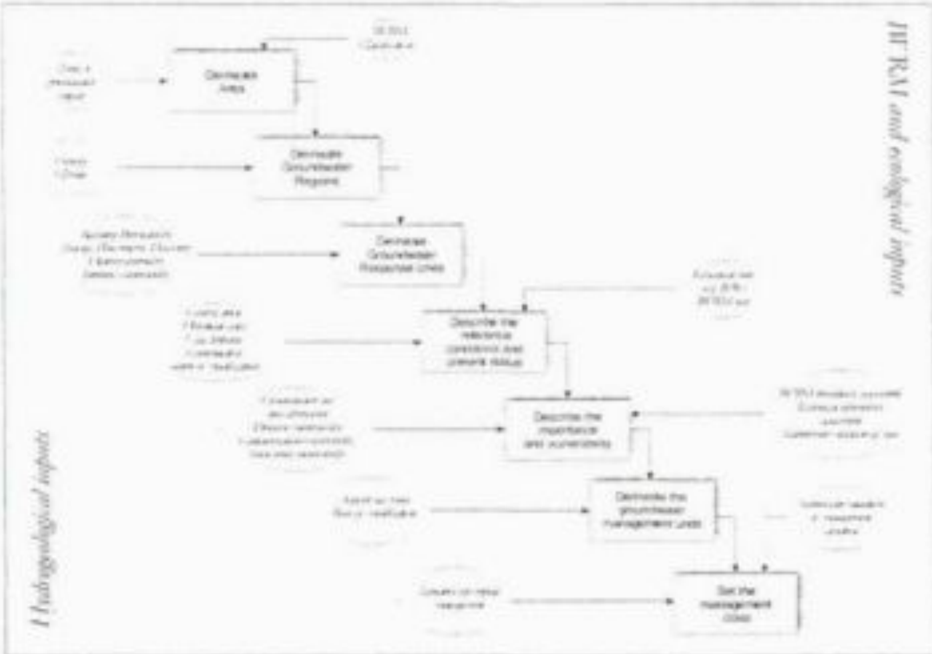

Figure 3.1: Stages of Groundwater Classification under the RDM.

Figure 3.1 shows inputs required to define each output from hydrogeologists and other IWRM contributers.

3.9 Define the geographic extent of the water resource

AIMS

- Identify significant water resources, or
- Identify the response unit and areas that will be impacted by a particular license application.
- Delineate geographical boundaries for the study.

Role of the groundwater specialist

To indicate the probable area of impact of the groundwater resource in question and highlight up- and down-gradient dependencies. This should influence the extent of the area chosen by the water manager for Classification.

3.9.1 Generic principles

Significance

The NWA states that the Minister must determine RDM "for all or part of every significant water resource". This should be done in a way which is practical for water use planning, allocation and licensing purposes, but which is at a scale which allows effective everyday management of the water resource itself (DWAF, 1999). The significance of the water resource is linked not only to its importance, but to its size (DWAF, 1999).

Scale

Once CMAs are established they will set up catchment management strategies which will include a strategy to implement protection measures for water resources, including the RDM. The progressive implementation of the RDM will eventually realise the classification of all significant water resources. However, the immediate roll-out of the RDM will be linked to license applications and prioritised to allow licences for water use to be processed in the context of resource protection. Classification may then occur at an aquifer or catchment spatial scale or be restricted to the probable zone of impact of a licence.

Boundaries

If the RDM determination is initiated by the Department as part of compulsory licensing process, then the boundaries are delineated by the relevant water management agency (DWAF 1999). Where an RDM determination is undertaken as part of the evaluation of an individual licence application, the study boundaries will depend on the nature, scale and extent of the impact of the proposed water use (DWAF, 2001).

Upstream-downstream dependencies may require that the study boundaries take account of additional water resources upstream or downstream of the study area (DWAF, 1999). Smaller units will be delineated further in the process of classification.

3.9.2 Considerations for groundwater

Significance

Groundwater resources which are significant in terms of their geographical extent, storage or local discharge need to be identified. This should be taken to be all groundwater resources in aquifers (strata with sufficient permeability to permit inflow to a borehole) which are perennial. Some perched, or ephemeral, aquifer systems are likely to be important for local ecological uses. Their perched nature will mean that they are unlikely to be connected to groundwater which will require a license for abstraction. But they may still be vulnerable to pollution and should be given protection where the ecological dependence is important.

Boundaries

Groundwater boundaries at a hydrological watershed or limit of a significant resource, may be complicated, with changing head/fixed head/ constant flux boundaries for several different layers. Also, secondary aquifer response units may not correspond with lithological boundaries. For some aquifers the recharge area may be outside the limit of the surface water catchment, but it may need to be considered in the management of the resource. The hydrogeologist needs to be able to sketch a probable conceptual model of these boundaries, noting estimated distal recharge and discharge zones.

3.9.3 Rules, tools and outcomes

RULE

Delineate significant (exploitable or ecologically important) aquifers in the area.

Or - Delineate significant (exploitable or ecologically important) aquifers within the probable zone of influence of a license application.

Tools

- Harvest Potential Map of South Africa
- Hydrogeological map series
- National Groundwater Database
- Local groundwater knowledge
- Local ecological knowledge

→ ***Outcome***

Initial delineation of relevant significant groundwater resources. This should be in GIS format. Record variable confidence in extent.

RULE

Describe in 3 dimensions the current broad understanding of the nature and extent of the relevant aquifers and their boundary conditions within the area.

Tools

- Geological maps.
- Hydrogeological map series.
- Local groundwater knowledge.

→ ***Outcome***

Initial delineation of boundary conditions of relevant significant groundwater resources in a preliminary 3D conceptual model. Record variable confidence in extent.

RULE

Identify probable areas of recharge and discharge for these aquifers (within the area and beyond its boundaries).

Tools

- Geological maps.
- Hydrogeological map series.
- Local groundwater knowledge.
- Local precipitation data.
- Local ecological knowledge.

- Local hydrological knowledge.

→ ***Outcome***

A preliminary 3D conceptual model showing the full delineation of significant groundwater resources in the area and their relevant extent with respect to up-gradient and down-gradient dependencies. GIS extent of area. Record probability of connection.

Parallel processes

These outputs will enable the Minister and Catchment Managers to effectively delineate the relevant (hydrogeologically connected) area for classification. Varying confidence in the probable continuity and dependence of distal areas will have to be assessed in the context of Integreated Water Resource Management (IWRM) priorities of the region.

3.10 Select the appropriate level of determination.

AIMS

- Select appropriate level of RDM determination.
- Select an appropriate study team.

Role of the groundwater specialist

To provide recommendations on the level of confidence required for groundwater classification based on a preliminary assessment of the importance and stress of the resource.

3.10.1 Generic principles

This relates principally to the level of confidence required in the results of the assessment, but also to the availability of relevant information. The confidence required depends on the nature, extent and probable impacts of the water uses for which the assessment and determination are undertaken, considered in the context of the ecological importance and sensitivity of the water resource in question (DWAF, 2001). Increasing levels of confidence imply increasing commitments of time and specialist inputs for, and therefore the costs of, each assessment.

Level of determination

Rules for selecting the appropriate level of RDM determination and the time taken are:

Desktop – *National Water Assessment Model.*

Rapid – *Individual licensing for small impact in unstressed catchments of low importance and sensitivity.*

Intermediate – *Individual licensing requirements in relatively unstressed catchments.*

Comprehensive *– Compulsory licensing; large impacts in any catchments; small and large impacts in very important or sensitive catchments.*

Levels of confidence in the results of determination are lowest with a desktop estimate and increase to the highest confidence in a comprehensive determination. However, it should be noted that even with a reasonable budget and an annual cycle of field data, the confidence in a comprehensive assessment may still only be moderate. This could be the case in areas where few historical data are available and the monitoring period occurred during a period of atypical conditions.

Comprehensive levels of determination will be carried out in more detail with significant budgets for field work and interpretation.

Study team

The composition of the study team depends on the level of the RDM study which is required, and the types of water resources which are included within the study boundaries. For a comprehensive determination, it may be necessary for each of the specialist sub-disciplines to be included. For rapid determinations, there may not be a need for separate representation of all the sub-disciplines (DWAF, 1999).

3.10.2 Considerations for groundwater

Study team

Too often the groundwater component of an RDM study is undervalued. The decision about which components need to be addressed and to what level, should be taken only after a multidisciplinary team, including a hydrogeologist, have compiled a draft 3D conceptual model of the catchment. This 3 dimensional approach is imperative to ensure adequate understanding of the role of groundwater. Typically, over 90% of water stored in a catchment is stored in aquifers. A preliminary assessment of the importance and degree of stress on groundwater quality and quantity will need to be made by a hydrogeologist. In addition, an impact assessment of proposed abstractions on any receiving environment and users should be made.

Figure 3.2: 3D Conceptual model of the catchment.(Source, USGS).

Level of determination

The level of RDM determination for groundwater should be carried out as indicated in the table below:

Levels of confidence in the results of determination are lowest with a desktop estimate and increase to the highest confidence in a comprehensive determination. However, it should be noted that even with a reasonable budget and an annual cycle of field data, the confidence may still only be moderate as discussed above. This is particularly true for groundwater in areas with high heterogeneity and few monitoring points. It is also true for groundwater resources found in the western areas of the country with high rainfall variability and susceptibility to drought. In these areas, monitoring and assessment over a drought cycle of several years may be necessary to assess the behaviour, vulnerability and sustainable yield of the resource with confidence.

The hydrogeologist should carefully track confidence in all assessments and assumptions and if necessary revise the RDM level at the end of the determination to suit the confidence in the results. This should be done with a clear indication of how the confidence in the assessment could be reliably improved.

As the methodology relies on expert judgement in many areas, the role of peer preview and review is very important. The reviewers should be considered an integral part of the team.

Table 3.1: Level of determination for groundwater classification.

Indicator	Aquifer type: Low yielding	Moderate yielding	High yielding
Sole Source dependency	Intermediate	Comprehensive	Comprehensive
Highly impacted	Intermediate	Comprehensive	Comprehensive
High risk of contamination or over abstraction	Rapid	Intermediate	Comprehensive
Moderate risk of contamination or over abstraction	Rapid	Intermediate	Intermediate
Moderately impacted	Rapid	Intermediate	Intermediate
No Sole Source depency	Rapid	Rapid	Intermediate
Low risk of contamination or over abstraction	Rapid	Rapid	Intermediate
Low impact	Rapid	Rapid	Intermediate

Key

Low yielding – *Harvest potential of < 10 000 m^3/km^2/annum or average borehole yields of < 1l/s*

Medium yielding – *Harvest potential of 10 000-50 000m^3/km^2/annum or borehole yields of 1-2 l/s*

High yielding – *Harvest potential of >50 000 m^3/km^2/annum or borehole yields of > 2 l/s.*

3.10.3 Rules, tools and outcomes

RULE

Estimate the approximate degree of importance, impact and risk posed to groundwater resources in the area.

Tools

- Expert knowledge.

→ *Outcome*

An understanding of the level of confidence required to protect the resource.

RULE

Estimate the degree of confidence in understanding the importance and vulnerability of the resource that will be achieved by Classifying groundwater over different time periods with different budgets, taking into account:

- Availability of existing data
- Availability of existing knowledge
- Degree of aquifer and landscape heterogeneity
- Number of sampling sites necessary to characterise the resource
- Expert knowledge

Tools

- Expert knowledge.

→ *Outcome*

An understanding of the feasibility of undertaking different levels of Classification with respect to the confidence required to protect the resource.

These outputs provide information for Table 3.1 and can lead to a recommendation from the groundwater specialist for the level of assessment necessary. Available resources may limit the assessment level undertaken.

3.11 Determine the eco-regional type (or types) and response units in the study area, and select survey sites

AIMS

- Determine groundwater regions and groundwater response units.
- Select sites for intermediate/ comprehensive RDM study

Role of the groundwater specialist

Describe the hydrogeological setting in the area, delineate areas with common hydrogeological characteristics and recommend sites for effective monitoring of reference conditions as well as compliance to Class.

3.11.1 Generic principles

Determine eco-regions

Eco-regions are areas in which there is relative homogeneity in geological and hydrological characteristics, and types of plants and aquatic animals. They enable some predictions to be made about the kinds of ecosystems which could be expected under natural or unimpacted conditions.

Eco-regional maps are being prepared for the whole South Africa (IWQS, 2001). The current scale of eco-regions is therefore national (Level 1), giving a broad characterisation of a catchment in terms of:

- Major physiographic factors, such as altitude, latitude, aspect, slope, climate zone;
- Geological factors, which determine geochemical signature as well as aspects of geomorphology and habitat;
- Regional natural hydrological characteristics, such as annual precipitation, seasonality and variability of flow;
- Major natural vegetation types (such as bushveld, lowveld etc);
- Biotic factors, including the natural occurrence of certain kinds of organisms such as fish, invertebrates, plants and algae.

Eighteen classes of eco-region are defined as shown in Figure 3.3.

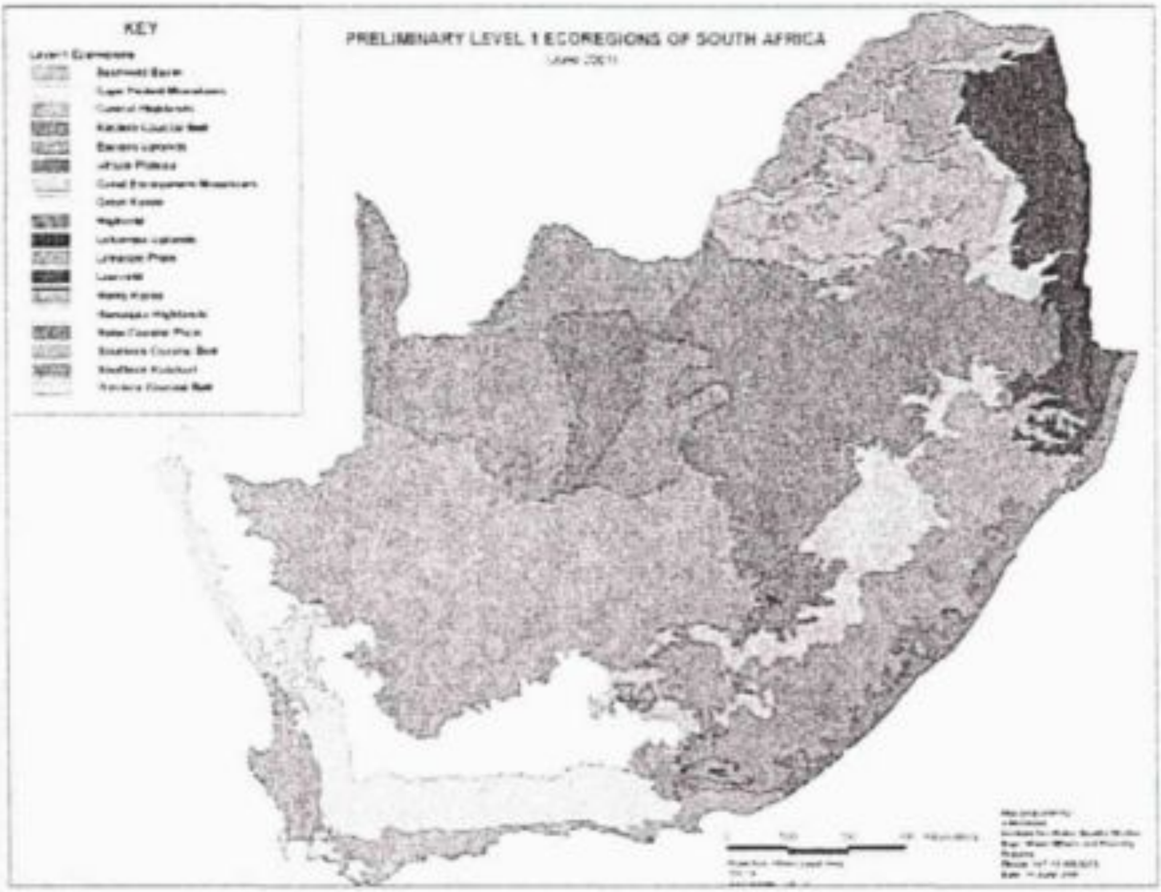

Figure 3.3: Preliminary level 1 eco-regions of South Africa.
For colour map see http://fred.csir.co.za/extra/project/groundwaterRDM/index.htm

Determine resource units within the study area

The breakdown of the ecoregion could be on the basis of the major land uses (DWAF, 1999). An example might be where markedly different land uses (such as agricultural and urban) occur along a reach of river which itself is all contained within one ecoregion. Each resource unit is sufficiently different from the other to warrant their own specification of the Reserve and RQOs, and to clearly delineate the geographic boundaries of each. This is because, for example, it would not be appropriate to set the same numerical Reserve for the headwaters of a river as for the lowland reaches: these sections of a river frequently have different natural flow patterns and chemical signatures, and require individual specifications of the Reserve appropriate for that reach (DWAF, 1999).

It is envisaged that the scale for resource units will be of the order of several kilometres of river reach (DWAF, 2002). The breakdown into resource units via ecoregions is then further resolved into smaller resource units which are suited to management requirements. A water quality resource unit is a length of river for which a single description of water quality can be given (DWAF, 2002).

Delineation of resources in the Reserve determination notice

The Government Gazette notice of the Reserve determination for a particular resource would refer to a map with the relevant water resource unit boundaries marked, and may be supported by map references (for example "the reach of the Crocodile River from the point A,B on the farm <name> to the point X,Y on the farm <name>").

If a notice was published containing the Reserve determination for an entire catchment, the notice would contain a list of delineated resource units within the catchment, together with the class, Reserve and RQOs applicable to each resource unit (DWAF, 1999).

Select survey sites within the study area

The selection of sites for specialist surveys is closely related to the various ecoregional types which may be represented in the study area, but also depends on other factors such as representivity, suitability for hydraulic calibration and accessibility.

The confidence in the determination of the RDM, is very much dependent on the selection of suitable study sites, and this step is one of the most important in the whole RDM determination. For water quantity and water quality Reserve determination, it may be adequate to select sites which cover more than one ecoregion. For determination of resource quality objectives for habitat and biota, the RQOs may need to be determined separately for each ecoregion.

3.11.2 Considerations for groundwater

Determine groundwater regions

Ecoregions are determined to infer some of the broad characteristics based on some of the more easily available biophysical data on the area. It is also useful to describe groundwater regions to indicate the broad hydrogeological category of aquifers in the area. This enables nationally consistent benchmarks to be progressively developed and an understanding of reference conditions for different climatic areas to emerge.

Groundwater regions could be given at the same scale based on similar biophysical attributes in order to characterise the aquifers in the area. Either existing geohydrological regions such as those classified by Vegter (1995) (Figure 3.4) or in the 1:500 000 hydrogeological map series (DWAF) could be used or a consideration of geology (lithology and structure, forming a hydrogeological terrain) (Figure 3.5), and climate (Figure 3.6) could be given for the area delineated.

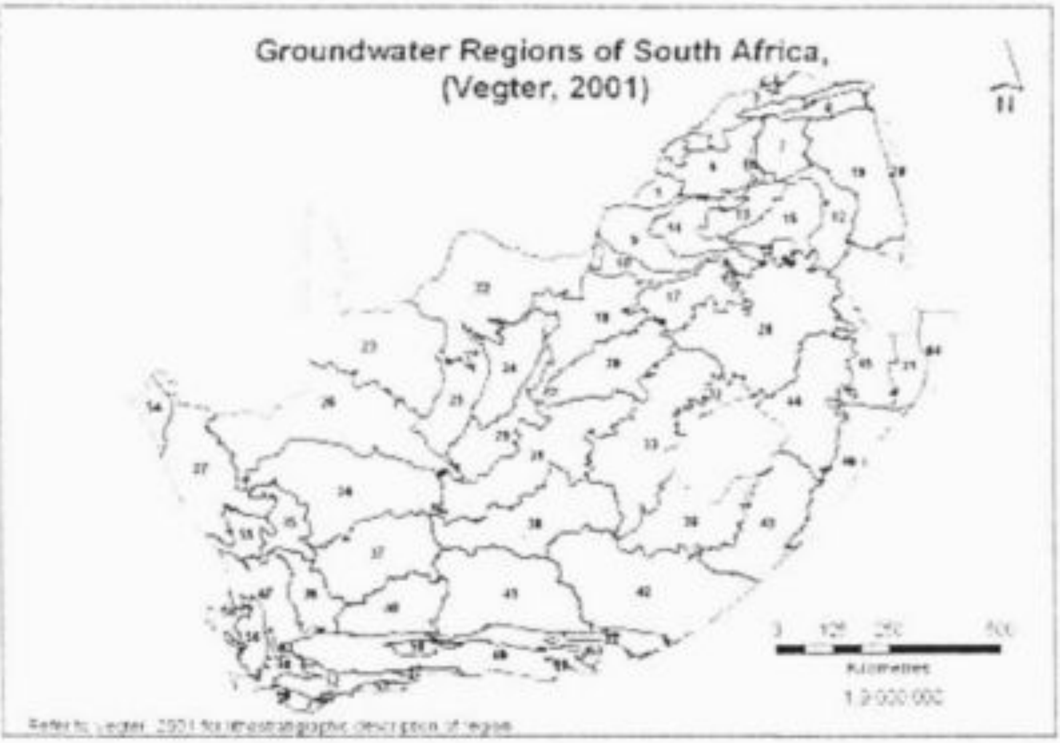

Figure 3.4: Groundwater regions of South Africa (Vegter, 1995)

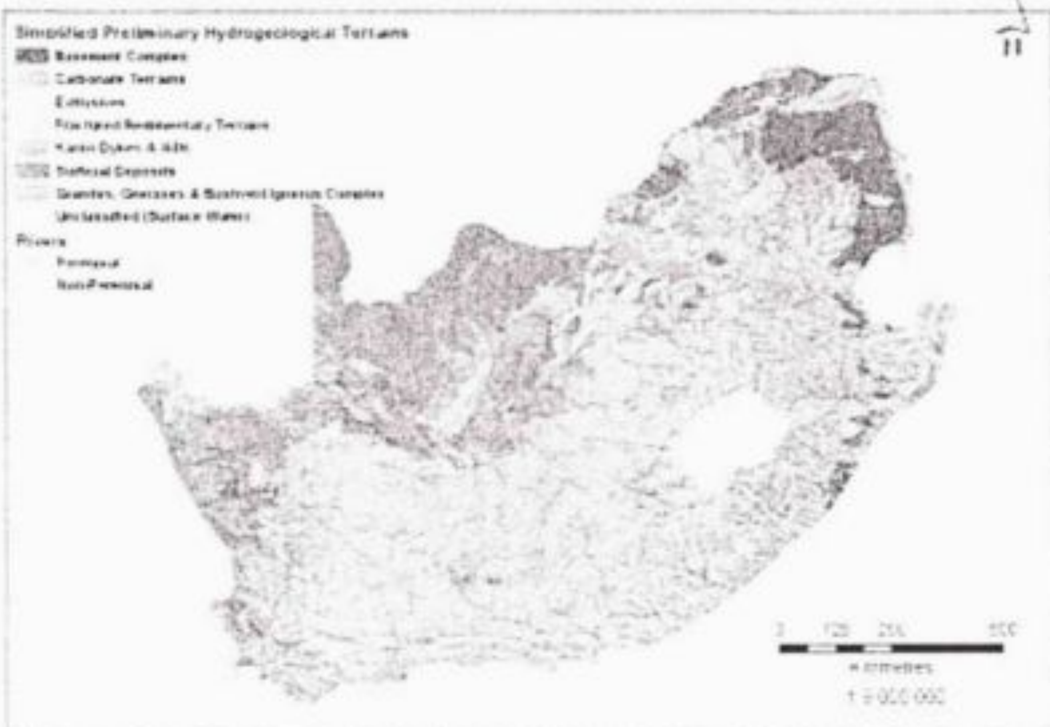

Figure 3.5: Preliminary hydrogeological terrains of South Africa. For colour map see http://fred.csir.co.za/extra/project/groundwaterRDM/index.htm

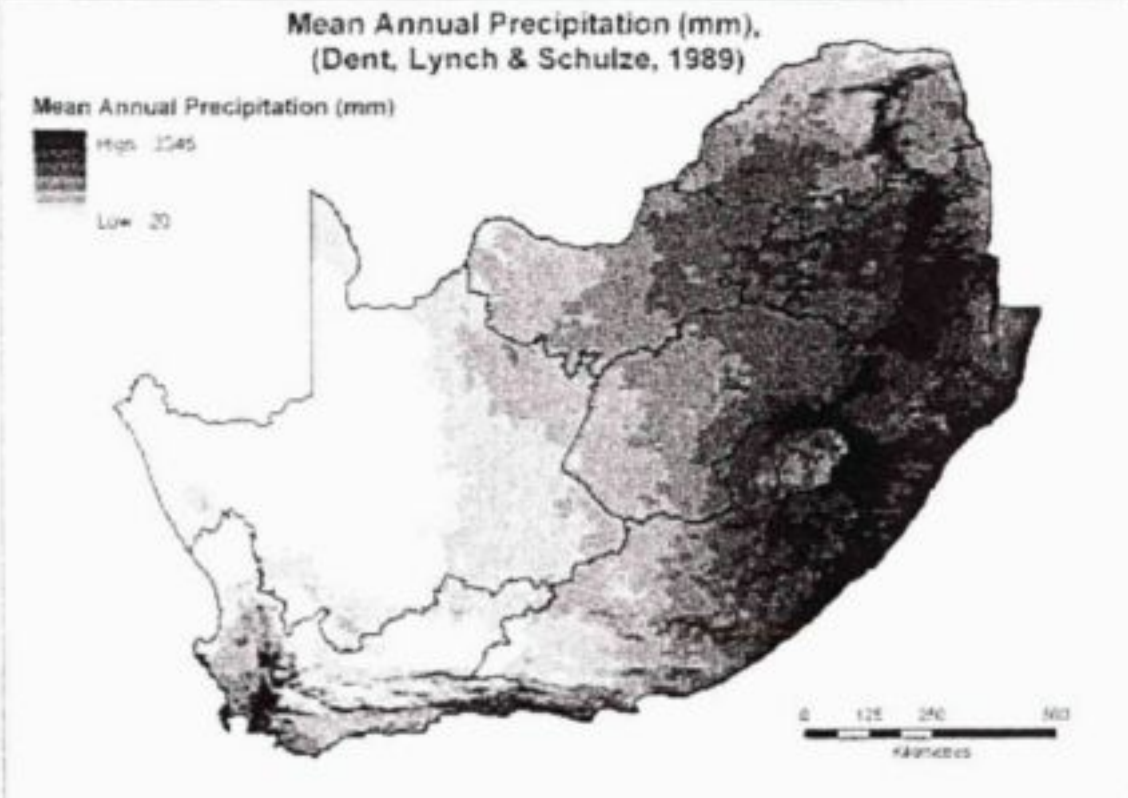

Figure 3.6: Mean annual precipitation in South Africa (Atlas of Agrohydrology, Schultze et al 1997).

Determine groundwater response units

Groundwater response units provide a useful, more detailed characterisation of groundwater units, based on a more detailed understanding of inherent physical hydrogeological attributes. These should include:

- Average recharge and sustainable yield;
- Aquifer lithology, permeability and approximate aquifer thickness;
- Hydrogeochemistry;
- Aquifer Storage;
- Water levels and a preliminary assessment of vulnerability to contamination from surface.

These should be defined based on all available information. NGDB and other drilling log information will be particularly useful. DWAF hydrogeological maps may be used for Rapid level classification. The level of confidence in each of the measured/ estimated parameters should be noted.

Groundwater response units are likely to occur at depth beneath surficial units. These should be inferred on the area map and 3D conceptual model.

Select study sites

As for surface water resources, the sites selected for study should be representative of the significant groundwater response units in the area. Field work will not be carried out for rapid level determinations and only a limited manner at existing sampling points for intermediate determinations. Sampling site selection is mainly relevant at comprehensive level determinations when data over one annual cycle may be gathered.

A differentiated approach to Classification monitoring is recommended with focus on:

- the most important and vulnerable groundwater management units;
- representative groundwater response units close to reference conditions (control monitoring)
- boundary conditions between different aquifer units and between groundwater and surface water resources (loosing /gaining /intermittent/ detached rivers; see chapter 4).

The monitoring should be focussed on particular parameters or attributes of the resource that are critical to its use. It is therefore recommended that the selection of monitoring sites and parameters should be finalised after an assessment of the importance and vulnerability of the groundwater resources has been completed in the following stage of the Classification process.

Newly constructed monitoring boreholes should be carefully constructed to sample correctly the groundwater response unit(s) required and the necessary parameters. Guidelines are given in the literature, e.g. – Guidelines and Standard Procedures for Studies of Groundwater Quality (USGS, 1997); Minimum Requirements for Water Monitoring at Water Management Facilities (DWAF, 1998); Contaminant Hydrogeology (Fetter, 1993), Draft Integrated Water Resource Management: Guidelines for groundwater management in water management areas of South Africa (DWAF, 2002).

Where existing boreholes are used, the hydrogeologist should carefully document their understanding of the borehole construction and confidence in the results acquired for different parameters.

Parallel RDM processes

Delineation of resource units for other components of the water system are likely to be happening in parallel to the delineation of groundwater regions and response units. Where relevant, groundwater monitoring should link to hydrological monitoring to enable a better quantification of groundwater – surface water interactions.

3.11.3 Rules, tools and outcomes

RULE

Based on the geology and climate of the area, delineate macro-scale (landscape) groundwater regions.

Tools

- Expert knowledge
- GIS overlay of climatic zones, geology, ecoregions level 1 (IWQS, 2001)
- Vegter's geohydrological regions (DWAF, 2001)
- 1: 500 000 hydrogeological maps

→ ***Outcome***

Catchment scale groundwater regional classification mapped in GIS

RULE

Based on inherent aquifer characteristics, delineate groundwater response units in the area.

Tools

- Expert knowledge
- Drilling and pump testing data (reports, NGWDB),
- Borehole prospects map,
- Hydrogeochemical data (TDS/ EC),
- Hydrogeological maps (1:500 000)
- National or regional DRASTIC maps
- Detailed geological maps.
- Land type maps

→ ***Outcome***

Local scale groundwater response units based on similar hydrogeological characteristics mapped in GIS. Record typical values for key characteristics, including range and heterogeneity.

RULE

Make an initial estimation of monitoring locations which will provide reference points and be representative of groundwater management units.

Tools

- Expert knowledge

→ ***Outcome***

Preliminary location of groundwater monitoring points.

The approach followed in this step is essentially the same for all levels of RDM. More time would be available for intermediate and comprehensive assessments and therefore more detailed on-site assessments should be made of groundwater use and impacts.

3.12 Determine reference conditions and assess present state

AIMS

- Determine resource quality reference conditions.
- Define the present state with respect to the degree of modification from the reference conditions.

Role of the groundwater specialist

The is one of the most involved steps for the groundwater specialist. S/he should predict the natural state of groundwater response units and estimate the degree of impact on groundwater resources in their present state.

3.12.1 Generic principles

Reference conditions – the natural baseline

Reference conditions describe the natural, un-impacted characteristics of a water resource. The assessment of present status and the selection of the future management class are carried out relative to the reference conditions for that resource. The reference conditions thus represent a **baseline** which is relevant to a particular resource. If the baseline is not stable, then the grounds on which management decisions are made will always be shifting (DWAF, 1999). This opens the door for de facto authorization of cumulative impacts in the water use licensing process, which is not consistent with the protection policy.

The reference conditions are set on the basis of un-impacted conditions, as that is the most stable baseline available. However, the parameters used to describe these conditions may have inherent variability. Natural fluctuations in water levels, concentrations of particular solutes and ecological structure need to be recognised.

It is frequently not possible to find an unimpacted site which can be surveyed, in order to accurately quantify reference conditions. **Expert judgement, local knowledge, historical data and analysis of measured historical trends** will often be necessary to build up a "picture" of the probable reference conditions, within broad confidence limits.

Reference conditions quantitatively describe the natural, un-impacted characteristics of the resource in terms of water quantity, water quality, geomorphology, vegetation and aquatic animals (DWAF, 2001). For groundwater resource reference conditions include information on water levels, and aquifer structure and composition (DWAF, 2001).

Reset baselines

There may be situations where the water resource has been modified to such an extent, and in such a manner, that ecosystem structure, functions and processes have been irreversibly changed.

Usually this is the result of permanent man-made changes to the physical structure and morphology of the resource, although sometimes it can be as a result of a catastrophic natural "reset" such as a very large flood.

The ecosystem can still be healthy and require protection in its present, highly modified state, although it may bear little resemblance to the ecosystem which was present under natural, un-impacted conditions. These areas may be classified as Severely Modified or 'artificial'.

An assessment of the present status of water resource quality (water quantity, water quality, habitat and biota) is needed in terms of the **degree of modification** from reference conditions.

Assessment of resource status and resource use

The revision of the generic methods from a surface water quality perspective has resulted in a slight change to the proposed number of classes to 5 (DWAF, 2002a).

1. Natural – relatively unimpacted.
2. Good – low impact from human disturbance
3. Fair – multiple disturbance and resource degradation
4. Poor – highly impacted and disturbed ecological functioning.
5. Artificial – modified beyond rehabilitation.

The full present status assessment is likely to match the full management classification system, in that it will address

- ecological status of the resource,
- status of the resource for basic human needs and
- status of the resource for water users.

3.12.2 Principles for groundwater

Natural baseline

Groundwater systems have been described as archives of the catchment, as the relatively slow transmission of responses through the system may preserve relic inputs from paleaoclimatic regimes. Thus for extensive, deep regional systems such as the TMG and Karoo, determining reference conditions may have to take very long term conditions into account.

If historical, pre- impact data are available, these will give the best indication of the reference conditions required under the NWA. Often anecdotal evidence is the only indication of pre-impact conditions. These should be used with an estimate of confidence.

Groundwater reference parameters

The key hydrogeological parameters that should be considered when giving groundwater reference conditions are:

- water levels in each groundwater response unit, and the seasonal and inter-annual variability of water level;
- water quality - the concentrations of key water quality constituents (related to the use of groundwater in the area) including:
  - TDS,
  - Fecal coliforms,
  - nutrients,

  and their seasonal and inter-annual variability;
- aquifer structure and composition, including:
  - aquifer integrity,
  - the pollution attenuation potential of the natural land types,
  - natural recharge rates and extent of recharge areas, and
  - natural discharge rates and the extent of discharge areas.

Groundwater reference conditions can be best summarised as a 3 dimensional conceptual model of the area with ascribed boundary conditions between groundwater response units, each other and the surface environment. This would include recharge and discharge areas and typical environmental uses of groundwater.

It should also include typical hydrogeochemical signatures for each unit and, at a comprehensive level, pristine aquifer integrity and attenuation potential.

Sample average annual hydrographs should be given for key response units. These may be derived by:

- deconstructing the current conditions (excluding abstractions, reconstructing recharge areas, etc);
- using historical data from pre-impact conditions;
- using information from similar groundwater response units in an un-impacted area.

Where the deconstruction method is used, this step of the RDM methodology becomes iterative with determining the present status category. It is often difficult to deduce the reference conditions, especially in potentially highly impacted areas. This process is intimately connected with the assessment of the present state.

The potential uses of natural quality groundwater should be listed with reference to the most sensitive parameters. It will also be useful to note uses which may not be met by groundwater under natural conditions due to the inherent characteristics of the resource.

Degree of modification of groundwater

Groundwater present status should be defined with respect to the degree of modification of the key attributes of resource units (Table 3.2). It is recommended that the overall assessment of

Table 3.2: Quantifying the present status of groundwater resources with respect to degree of modification.

Present Status Category	Degree of modification Nature	Extent	Duration	Significance (w r t Use)
Natural	Positive/negative/ none	Localised	Limited	None
Good	Negative	Localised	Limited	Low
Fair	Negative	Localised	Medium term	Moderate
		Widespread	Limited	
Poor	Negative	Localised	Long term	High
		Widespread	Medium term	
Severe	Negative	Localised/ widespread	Irreversible	High

modification indicate any change in the functionality of groundwater, in other words changes to the goods and services, that groundwater fulfils.

The most obvious benchmark parameters are water levels, TDS, microbial quality, contaminant concentrations, and aquifer integrity. Determining the degree of modification of these parameters from reference conditions needs to be linked current and potential groundwater uses. A parameter such as water level may be described in terms of the percentage modification from reference conditions (in metres below ground level). TDS on the other hand will have certain threshold limits that control its use and the category of modification needs to be linked to these thresholds.

It needs to be noted that pristine groundwater quality and quantity may be of limited use in areas where the sustainable yield is low and the natural quality poor. In some areas, pristine resources may not be fit for many uses, such as drinking water and irrigation.

At this stage the groundwater specialist should make an inventory of all groundwater uses. The uses should include:

- all activities which are likely to impact groundwater;
- all extractive uses of groundwater;
- all environmental uses of groundwater in terms of baseflow and transpiration.

The assessment of environmental uses will require the input of local ecologists.

In terms of assessing impact, an approach aligned to accepted Environmental Impact Assessment methods are recommended. The degree of modification, that is the Present Status, should be determined with respect to the estimated nature, extent, duration and significance of the change. The Present Status category should be assessed as indicated in the table below (Table 3.3).

Key

Limited duration – natural attenuation/water level recovery < 2 years

Table 3.3: Relating groundwater key attributes to reference conditions and present status. per groundwater response unit (Eg from Nardouw response unit in Kammanassie example)

Attribute	**Predicted reference condition**	**Impacting uses**	**Nature and extent of impact**	**Present status (Modification)**
Mean water levels and range (mbgl)	Artesian-120mbgl	Domestic wells, irrigation and stockwatering	Accumulated drawdowns	70-150mbgl Poor
Hydrogeochemical facies	NaCl	Not known	None	Natural
Mean TDS and range (mg/l)	>100	No	Relatively large scale	100-899[1] Good- poor
Distinctive hydrogeochemical signature (eg – naturally high NO3)	Fe-bearing lithologies	No	(borehole clogging)	Natural
Baseflow to rivers and estuaries (location and seasonal volumes if known)	At litho/structural contacts	Abstraction for irrigation and from KKRWSS	Localised	Fair
Baseflow to springs and wetlands (location and seasonal volumes if known)	At litho/structural contacts	Abstraction for irrigation and from KKRWSS	Localised	Fair
Cryptic discharge to vegetation	Near springs	Abstraction for irrigation and from KKRWSS	Localised	Fair
Mean annual recharge (location and seasonal volumes)	10 Mm^3/a (low confidence)	(Climate change?) Abstraction may increase recharge	(Widespread?) Localised	Natural/ Good
Mean annual discharge (location and seasonal volumes)	2 Mm^3/a	Abstraction	Moderate	Fair
Potential for drinking water use.	Fair (TDS values high)	Abstraction	Local decrease in quantity	Natural
Potential for irrigation use.	Good	Competing abstraction (Climate change?)	Widespread Moderate	Fair

Medium term – natural attenuation/ water level recovery >2 years < 10 years

Long term – natural attenuation/ water level recovery > 10 years

Low significance – Localised seasonal impact on use, non-critical.

Medium significance - Localised medium term or widespread seasonal impact on use, non-critical.

High significance – Critical impact on use, i.e. no alternate resources available and functioning of ecological or socio-economic activity is threatened.

See Appendix A for more discussion of this example.

- Describe the natural attenuation capacity of recharge areas in terms of the characteristics of the unsaturated zone and DRASTIC (Aller et al. 1988).
- What is the level of confidence in the designated reference conditions?
- What are the direct and indirect uses of groundwater in the area?

The following activities are described under the NWA as uses -

(a) taking water from a water resource;
(b) storing water;
(c) impeding or diverting the flow of water in a watercourse;
(d) engaging in a stream flow reduction activity contemplated in section 36;
(e) engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1);
(f) discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;
(g) disposing of waste in a manner which may detrimentally impact on a water resource;
(h) disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process;
(i) altering the bed, banks, course or characteristics of a watercourse;
(j) removing, discharging or disposing of water found underground if it is necessary for the efficient continuation of an activity or for the safety of people; and
(k) using water for recreational purposes.

- What is the significant of impacts on groundwater from indirect and direct uses?
- Do present uses pose an increased risk to aquifer integrity, drought or contaminant vulnerability

3.12.3 Rules, tools and outcomes

RULES

Estimate the level of use of groundwater in the relevant area with respect to::

- **Basic human needs**
- **Aquatic and terrestrial ecosystems;**
- **Schedule 1 activities (NWA 1998);**
- **General authorisations (Government Gazette 20526, 1999);**
- **Other extractive uses;**
- **Contamination of groundwater;**
- **Mean annual recharge.**

Tools

- Population statistics (SSA)

- Local ecological, hydrogeological and hydrological knowledge
- National Groundwater Database
- Water Use Authorisation Management System (WARMS)
- Groundwater classification map (Parsons and Conrad, 1995)
- Water Situation Assessment Model (WSAM)
- Recharge estimates from local knowledge or National groundwater maps (Vegter, 1995)
- Basic water balance estimation for the relevant resource.
- Harvest potential map (DWAF, 1996)

→ ***Outcome***

- *An inventory and map of groundwater use in the area.*
- *Initial understanding of the importance of the groundwater in the area.*

RULES

Determine groundwater reference conditions.

Tools

- Expert knowledge to un-impact (forensic hydrogeology) the current conditions (excluding abstractions, reconstructing recharge areas, etc) using basic water balance approach for rapid/ intermediate levels and numerical modelling if appropriate for comprehensive level.
- Analyse historical data from pre-impact conditions (NGDB, NWQB)
- Anecdotal information.
- Extrapolate information from similar groundwater response units in an un-impacted area.
- Assess probable impacts from Land Cover Maps (1:250 000) (CSIR, 1999) and uses (above).

→ ***Outcomes***

- *'Naturalised' 3D model of groundwater response units' reference conditions and their boundaries.*
- *This may be a numerical model for selected areas in a comprehensive determination.*
- *Un-impacted typical response unit hydrographs.*
- *Natural range of hydrochemistry for groundwater response units.*

RULES

Determine the present status of groundwater management units by assessing the significance of impacts (Tables 3.2 & 3.3).

Tools

- Expert hydrogeological knowledge.
- Expert ecological and economic knowledge of the impacted area.
- NGDB, NWQB, local groundwater databases, monitoring outputs of the determination.

→ ***Outcomes***

- *Map and 3D conceptual model of the area with assigned present status.*

3.13 Describe the importance of the resource

AIMS

Determine importance of resource units, with respect to:

- Ecological importance
- Social importance
- Economic importance.

Role of the groundwater specialist

The groundwater specialist has a relatively minor role to play in this stage. They should draw in the relevant ecologists, stakeholder representatives and resource economists to assess the importance of the various uses they have defined in determining the present status.

3.13.1 Generic principles

Ecological importance

The ecological **importance** of a river means its importance to maintain its ecological diversity and functioning on local and wider scales. In determination of RDM, the following ecological aspects are considered as the basis for the estimation of ecological importance and sensitivity:

- The presence of **rare** and endangered species, unique species (i.e. endemic or isolated populations) and communities, intolerant species and species diversity.
- Habitat **diversity**, including specific habitat types such as reaches with a high diversity of habitat types, i.e. pools, riffles, runs, rapids, waterfalls, riparian forests, etc.
- The importance of the particular resource unit (e.g. river or reach of river) in providing **connectivity** between different sections of the whole water resource, i.e. whether it provides a migration route or corridor for species.
- The presence of conservation areas or relatively **natural areas** along the river section.

Procedures for rating ecological importance and sensitivity are given in detail in each specialist manual.

Social importance

Aspects to be included in the assessment of economic and socio/cultural importance are:

- the extent to which people are dependent on the natural ecological functions of the water resource for water for basic human needs (sole source of supply),
- dependence on the natural ecological functions of water resource for subsistence agriculture or aquaculture;
- use of the water resource for recreation;

- the historical and archaeological value of the water resource;
- its importance in rituals and rites of passage;
- sacred or special places in the river (e.g. where spirits live);
- the use of riparian plants (for building or traditional medicine), and
- the intrinsic and aesthetic value of the water resource for those who live in the catchment, or who visit it.

Social importance can be assessed within a similar framework as that for ecological importance, but in a much more qualitative manner. The methodology is described in Rivers Appendix R8 (DWAF, 1999). Although some element of subjectivity is inevitable in value assessments such as these, the results are intended to be as objective a reflection of relative importance as possible. They are not intended to be subject to complex statistical analysis, nor to measure social values with precision, but to capture a general feeling of the importance of different aspects of a river.

Economic importance

Water resources are usually important from an economic point of view. The economic value of a water resource is traditionally assessed in terms of the amount of water which can be abstracted for offstream use. Typical indicators include the number and value of jobs generated by the use of the water, or the amount of revenue generated.

Water resources also provide other services which are often not included in economic valuation, and in particular this applies to the services and benefits provided by aquatic ecosystems.

These can include, amongst others:

- transport and/or purification of biodegradable wastes;
- recreation and aesthetic opportunities;
- food production;
- flood attenuation and regulation;
- water-based transport.

While the development of tools for quantitative valuation of ecosystem services and benefits is still in an early stage, it is necessary that all the potential economic values of a water resource at least be identified when assessing economic importance.

Additional detail on possible methodologies for assessing economic importance can be found in Rivers Appendix R9 (DWAF, 1999).

3.13.2 Principles for groundwater

Ecological importance

The sensitivity of ecosystems which use groundwater is often linked to their dependency on groundwater above other sources of water. Some ecosystems may use groundwater opportunistically, it may even supply the bulk of their water use, but we need to pose the question: How would the ecosystem react if groundwater were not available or were severely modified? Sometimes soil moisture or surface water will be used by the ecosystem with negligible long term impact on the environment. This issue is discussed in more detail in the companion draft report *Assessing Terrestrial Groundwater Dependent Ecosystems in South Africa*, Colvin *et al*, 2002.

Groundwater may play an important role in terrestrial and aquatic ecosystems in terms of providing:

- water, particularly during dry periods;
- nutrients;
- trace elements.

Social importance

Importance of the resource should be determined by the stakeholders in comprehensive determinations. In the case of groundwater, this may require some effort for public education in order to improve stakeholders' understanding of the full role groundwater plays in their environment and economy.

Economic importance

The principles of resource economics outlined above should be applied to groundwater as well as surface water. A quantification of the social, environmental and economic importance of aquifers should be made. In addition, the strategic value of groundwater as a relatively drought resilient resource with greater buffered storage needs to be taken into account. Replacement costs should be determined for groundwater: What would it cost to replace the goods and services offered by groundwater if it were not available (especially in times of drought)? Economic importance may be valued in rand terms and considered more qualitatively in terms of local, regional, national, seasonal and strategic value.

Importance:

- Qualitative - Local, regional, national, seasonal, strategic.
- Quantitative – Rands or product per litre, downstream valuation of environmental services.

The groundwater specialist should pose the question: What would happen if groundwater were not available? What is the dependency of uses on groundwater:

- High – cease use in absence of groundwater.
- Moderate – costs increase, reliability decreases.
- None – alternate sources of water would be used with no impact on availability and cost of services.

Parallel RDM processes

The outputs above will critically inform the overall output of this stage which includes other specialists and stakeholders.

3.13.3 Rules, tools and outcomes

RULE

Characterise the current and potential (future or natural) uses of groundwater in the area for consideration by the stakeholders.

Tools

- NGDB, Hydrocensus, WARMS
- Groundwater Dependent Ecosystem (GDE) assessment.

→ ***Outcome***

- *A map showing the distribution of different uses, including areas of overlapping use (potential competing demand).*
- *An inventory of the uses including estimated volumes required, water quality thresholds and water level thresholds.*

RULE

Estimate the importance of groundwater resources in the catchment with respect to current and probable future uses.

Tools

- Integrated Development Plan for the area.
- Available Strategic Environmental Assessments (SEAs)
- Water Resources Situational Assessment
- Specialist inputs for different water components.

→ ***Outcomes***

- *A map showing the distribution of different uses of all water resources, including areas of overlapping use (potential competing demand).*
- *A ranking of all uses in terms of their social, economic and environmental importance in the area*

3.14 Determine the sensitivity or vulnerability of the resource

AIMS

- Determine the vulnerability of resource units to contamination, over-exploitation and subsidence.

Role of the groundwater specialist

The groundwater specialist has an important role to play in defining aquifer vulnerability and quantifying this as far as possible. This assessment needs to be communicated to stakeholders and *decision makers to inform their decision on the ultimate level of protection required to maintain desired uses of groundwater. Aquifer vulnerability to contamination, subsidence and over-exploitation needs to be understood in the context of risks posed by activities in the catchment.*

3.14.1 Generic principles

Ecological sensitivity

Ecological **sensitivity** (or fragility) refers to the system's ability to tolerate disturbance and its capacity to recover. Additional detail on possible methodologies for assessing economic importance can be found in Rivers Appendix R9 (DWAF, 1999).

3.14.2 Principles for groundwater

Groundwater vulnerability

A full assessment of groundwater vulnerability should include:

- Vulnerability to contamination from surface;
- Subsidence risk and vulnerability of aquifer integrity;
- Vulnerability to groundwater drought, and
- Vulnerability to over-exploitation.

The risk posed to groundwater determines

Contamination vulnerability

Groundwater vulnerability is typically considered in terms of the DRASTIC method of assessment of intrinsic vulnerability of an aquifer to **contamination** from the surface (Aller et al, 1987). This considers the features of a groundwater system that control the vulnerability of an aquifer to contamination from surface:

- Depth to water table
- Recharge
- Aquifer material
- Slope
- Topography and slope
- Hydraulic Conductivity

The DRASTIC method is widely accepted but has inherent subjectivity due to the selection of classes and weights for characteristics. The use of this method has not been validated in South Africa (Sililo and Saayman, 2001). However, it is generally found to be useful, especially in determining relative vulnerability.

A modified version of this assessment has been applied at a national level by Reynders and Lynch, 1993, and this is appropriate for rapid level determinations. More detailed, modified DRASTIC determinations may be needed for comprehensive RDM at the scale of groundwater response zones where it is indicated that vulnerable groundwater is at risk from contaminating activities.

Detailed soil and aquifer matrix attenuation potential information is rarely available to groundwater specialists. Sililo *et al* outline a method to use existing land type data in order to infer cation and anion attenuation potential (Sililo *et al*, 2000). The project team have not found this to be an easy process to repeat, mainly due to data attribute problems.

In South Africa's predominantly secondary aquifer setting, it is vital to include controls of fracture vulnerability in an assessment. This can be done at a local and catchment scale by assessing lineament density. In addition, lineament connectivity at surface and depth and the expected nature of lineaments with depth may be taken into account where this is understood sufficiently to add value to the vulnerability assessment.

In all cases of vulnerability assessment, it is recommended that the basic DRASTIC approach is modified to the local hydrogeological setting and data availability. Fracture features should be included where appropriate. The modifications as well as weighting given to each factor should be justified. The expected heterogeneity of each factor within the setting and the resolution of measured or inferred values should contribute to a review of confidence in the assessment.

Appendix A discusses the application of a modified DRASTIC approach to an area with secondary and primary aquifers. The GIS outputs of the process are shown in the figures in the appendix.

In order to understand the risk posed to groundwater it is necessary to determine not only the intrinsic vulnerability of the resource to contamination based on hydrogeological characteristics, but also anthropogenic controls on risk such as

- the presence of potentially contaminating activities in vulnerable areas, and
- the level of groundwater and land-use management practiced in the area.

For intermediate and comprehensive levels of determination we need to assess potential **hazards** and impacting activities. These may be rated according to the likely degree of impact on groundwater quality. It is only once we have a balanced assessment of vulnerability and hazards that we will have an idea of the risk posed to the resource. This will give an indication of the achievability of certain levels of protection. This is demonstrated in Appendix A, where land-fill waste sites are ranked highest and protected natural land ranked lowest, with various types of agriculture and urban land-use in between.

The effectiveness of catchment management structures to mitigate risks posed to groundwater resources are more difficult to assess, but this issue should be addressed in terms of Classification.

Over-exploitation

In addition to the vulnerability of water quality, the vulnerability to **water quantity** impacts and impacts on aquifer integrity need to be considered. Over-exploitation is taken to mean use, typically abstraction, of the aquifer beyond its sustainable limits. This may result in declining water levels, saline intrusion and loss of functioning of the aquifer.

Indicators for vulnerability to over-exploitation can be summarised in terms of :

- Competing uses of groundwater
- Over abstraction (abstraction > mean annual recharge or having undesired impacts)
- Drought susceptibility
- Limited understanding of the resource characteristics
- Lack of groundwater management.

Drought

Often important groundwater uses, such as for Basic Human Needs or environmental uses, are linked to the ability of aquifers to provide water during dry seasons or periods of drought. In these cases, aquifers have an importance and provide strategic benefits which are much greater than their proportional contribution to the average water budget of the catchment.

The drought vulnerability of aquifers in terms of their storage and location in areas of less reliable rainfall and recharge should be considered. Areas with a low rainfall and a high coefficient of variation for annual precipitation are more likely to suffer groundwater droughts. Vulnerability to drought should be assessed in terms of:

Hydrogeological indicators:

- Aquifers with low storage and thickness.

Physical Indicators:

- Sustained inadequate (below average) rainfall.
- High variability in low rainfall areas.
- Reduction in the frequency of rainfall events thought to cause groundwater recharge.
- Failure of surface water sources during periods of drought.

Social Indicators:

- Increased demand for groundwater to meet irrigation and other needs
- Over-utilisation of groundwater at a time of diminished recharge.
- High degree of dependency on groundwater.
- Lack of drought planning in water management systems.

Table 3.4: Concepts of over-exploitation of groundwater (Custodio, 2000).

Safe Yield
Strict: abstraction < recharge
Expanded: abstraction that does not produce undesirable effects

Sustainable Use
Development that satisfies present needs without compromising the ability of future generations being able to satisfy their own needs.

Overexploitation
Strict: abstraction ≥ recharge
Expanded:: development that produces undesirable effects on

Water quantity
- Drawdown of
  - Water table
  - Piezometric levels
- Decrease of (freshwater) in storage
- Reduction of
  - Spring flow
  - Base flow

Water quality
- Increasing salinity
- Appearance of hazardous components
- Enhanced pollution and contamination

Environment
- Reduction / Dispaition of
  - Wetland surface area
  - Groundwater-dependent vegetation
  - Springs and seepages

Water cost → it increases
Groundwater availability → it decreases

Land stability
- Subsidence
- Cracking
- Collapses

Social perception → something wrong happens
Temporality → water is unavailable when needed

They may appear even if abstraction < recharge

Mining
Strict: Abstraction >> recharge
Expanded: freshwater reserves reduces at a fast pace

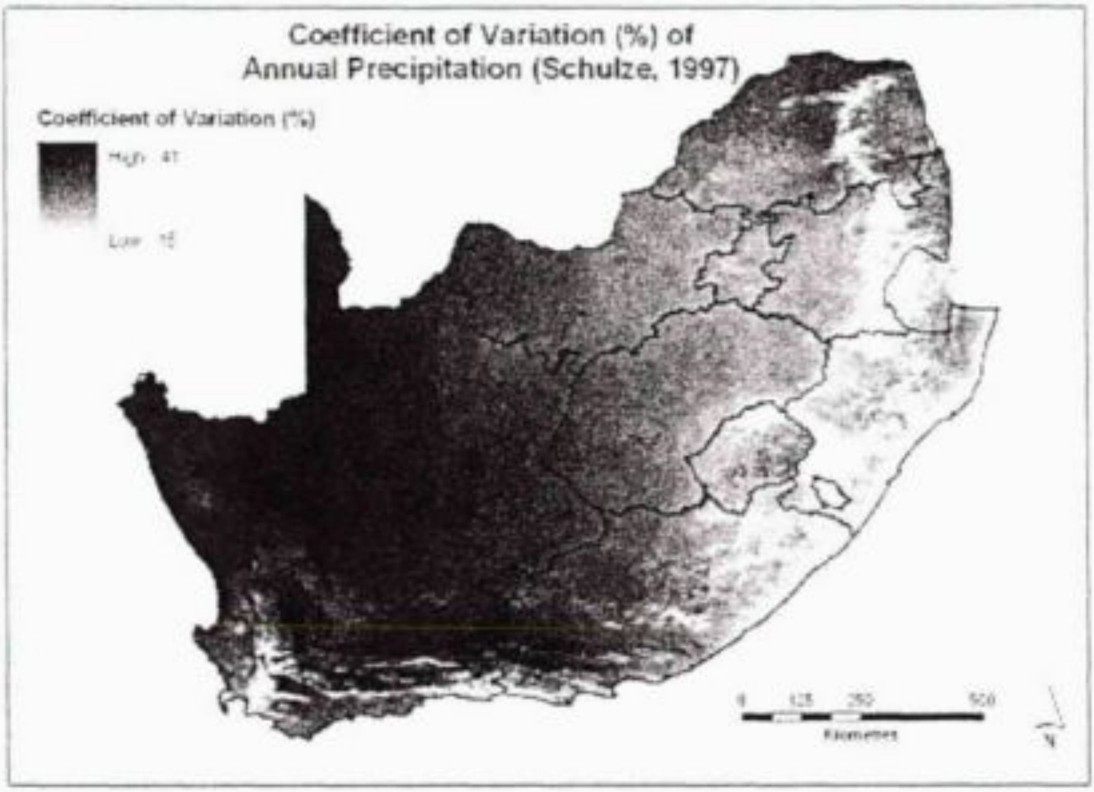

Figure 3.7: Coefficient of variation of mean annual precipitation in South Africa. (Atlas of Agrohydrology, Schultze et al 1997).

Aquifer integrity

Aquifer matrix stability with respect to declining water levels and subsidence should be considered. This is only known to be a problem in the dolomitic areas of South Africa (Brink, 1979). In these areas, subsidence risk should be assessed from existing information (Council for Geoscience) or available subsidence risk maps.

Aquifer subsidence occurs when the abstraction of groundwater results in a disturbance of the equilibrium of the soil or rock structure, with a resultant reduction in the sub-surface pore space in the aquifer. Land subsidence is the lowering of the land-surface elevation as a result of underground changes.

Consequences of land subsidence include:
The permanent loss of groundwater storage, damage to highways, buildings, and other structures, changes in groundwater and surface water flow patterns, groundwater quality deterioration and salt-water encroachment, localized flooding, and the collapse of borehole casings.

Indicators for increased risk of subsidence in South Africa include:

- The presence of dolomitic aquifers.

- Declining water levels in these areas.
- Potential for leaking water pipes (increasing dissolution rates).
- Gravitational lows associated with low density material.

3.14.3 Rules, tools and outcomes

RULE

Assess the vulnerability of groundwater response zones to contamination.

Tools

- DRASTIC map, 1993.
- Hydrogeological map series.
- Water levels
- Land type maps of soil cover.
- Expert knowledge of aquifer and soil properties with respect to attenuation.
- Estimation of land-use and potential hazards.
- Monitoring data.

→ ***Outcome***

GIS map of DRASTIC or modified DRASTIC assessment of contamination vulnerability overlaying groundwater response zones. Record data sets, resolution and reasons for modifications.

RULE

Assess the vulnerability of groundwater response zones to drought.

Tools

- Weather Bureau of SA precipitation data.
- Water levels
- Previous outputs of use.
- Assessment of drought-preparedness for water management institutions.

→ ***Outcome***

GIS map of drought vulnerability overlaying groundwater response zones. Record of confidence

RULE

Assess the vulnerability of groundwater response zones to subsidence.

Tools

- Location of karstic/ dolomitic aquifers
- Degree of modification of water levels
- CGS subsidence risk maps
- Gravity surveys.

→ ***Outcome***

GIS map subsidence vulnerability (where applicable) overlaying groundwater response zones.

RULE

Assess the vulnerability of groundwater response zones to over-exploitation.

Tools

- Drilling logs and pump test data
- Previous output of inventory and map of groundwater use
- Water resource use situational analysis.
- Previous output of drought vulnerability
- Assessment of water management systems wrt sustainability.

→ *Outcome*

GIS map vulnerability to over-exploitation in preliminary groundwater management areas.

3.15 Set the management class

AIMS

Set the management classes for groundwater management units taking into account the needs for:

- Ecosystem protection
- BHN protection
- Water users' protection

And based on:

- Importance
- Sensitivity/Vulnerability

Achievability (Present Status)

Role of the groundwater specialist

At this stage the groundwater specialist should present the outputs of previous stages to inform the stakeholder decision to set the management Class. It is the responsibility of the groundwater specialist to ensure that the decision makers take due account of the importance and vulnerability of groundwater in the area and understand the consequences of setting a particular level of protection.

3.15.1 Generic principles

Setting a management goal

This stage entails the selection of an appropriate management class as the target for long term protection and management of the resource unit. This could be the same as the present status category, or it could be set higher if improvement of resource quality is required.

Resource quality specifications become RQOs with the addition of time frames, responsibilities and strategies for achievement, and compliance criteria. Because resource quality specifications may be different parts of the resource, RQOs must also clearly state the geographical area in which they will apply. RQOs may also deal with the regulation or prohibition of instream or land-based activities which may affect the quality of the resource (DWAF, 2002a).

Testing the implications of selecting a particular management class

Each management class has associated with it rules concerning the derivation of numerical objectives for the Reserve and resource quality. Hence the implications of selecting a particular management class can be established and various scenarios tested before the final class is set.

It is likely that there will be some iteration around selection of a possible management class and the evaluation of the implications for the Reserve and for source control measures, until a management class is selected which represents the optimal balance between protection and utilization.

Classification rules for ecosystems, basic human needs and water users

The water resource classification system, when fully developed, will have three aspects: it will set out clear rules for

- protection of basic human needs, according to the five water quality classes for basic human needs set out in the Assessment Guide (DWAF, DOH & WRC, 1998);
- protection of aquatic ecosystems, according to the four ecological management classes, and
- water user requirements, according to the water quality ranges given in the South African Water Quality Guidelines (DWAF, 1996).

Criteria for selecting a future management class

Criteria for selecting a class for a water resource include:

- the sensitivity of the resource to impacts of water use (whether due to ecological sensitivity, or the sensitivity of downstream water users);
- the importance of the resource, in ecological, social/cultural or economic terms;
- what can be achieved towards improvement of resource quality, given that some prior impacts or modifications may not be practically reversible due to technical, social or economic constraints.

Water resources will, as far as possible, be managed so as to maintain them in their present ecological condition (that is, within the boundaries of their ecological class). However, in some cases there may be pressing social and economic reasons to permit short-term uses which will cause limited degradation of resource condition, and these will be considered on their individual merits.

Protected class

Protected: A Protected resource will be one in which:

- Human activity has caused no or minimal changes to biological communities (animals and plants), to the hydrological characteristics, or to the bed, banks and channel of the resource.
- Chemical concentrations are not significantly different from background concentration levels or ranges for naturally occurring substances; and
- Concentration levels of artificial substances do not exceed the detection limits of advanced analytical methodologies.

All of the above conditions must be satisfied. Criteria for classification as Protected will include: national or international heritage site or areas; biodiversity; the Ramsar Wetlands Convention; economic (tourism, medicinal plants) and social/cultural considerations; and areas designated as Protected under any other legislation."

The Protected class is a reference condition. Resources in other classes will be defined in terms of the degree of deviation from conditions of no or minimal impact.

Good class

In which the condition of the resource is slightly to moderately altered from the Protected, reference conditions.

Fair class

In which the resource has been significantly changed form reference conditions.

Water resources will, as far as possible, be managed to maintain them in their present ecological condition (that is, within the boundaries of their ecological class). However, in some cases there may be pressing social and economic reasons to permit short-term uses which will cause limited degradation of resource condition, and these will be considered on their individual merits.

Some resources are already in a condition which may be described as Poor (that is, worse than Fair). In these cases the management class will be set as (at least) Fair, and management efforts will aim to rehabilitate the resources to an improved condition.

Severely modified class

In addition, some water resources have been so severely and permanently physically modified that rehabilitation to anything approaching a natural ecosystem would be impossible or prohibitively expensive. Such resources, or parts of resources – rivers which have been canalised through urban areas, or for flood protection, for example – may be classified as **Severely Modified**. The classification system will provide for the development of resource quality objectives for Severely Modified resources but, as they cannot be regarded as functional ecosystems, the procedures will not involve the determination of an ecological Reserve.

3.15.2 Principles for groundwater

Setting the management class is a management and **stakeholder decision** that should be informed by the outputs of the previous stages.

Corresponding to surface water resource units, groundwater management units will represent areas of similar hydrogeological characteristics (groundwater response units) and similar use. They will delineate an area where consistent management actions are required to maintain level of use and protection for the aquifer.

In order to define the area, it will be necessary to understand :

1. the hydrogeological characteristics (groundwater response unit)
2. current and probable future uses of groundwater,
3. potential hazards to groundwater use,
4. the importance of the use to stakeholders,
5. the level of protection for that function desired by stakeholders (RDM Class),
6. measurable attributes of the resource that maintain its desired functioning (Resource Quality Objectives)
7. and the area where these attributes need to be managed to safe guard that function (management units).

In representing areas of consistent aquifer protection management, groundwater management units will have variable extent. Some areas of intensive multiple use or highly variable vulnerability, may require localised management over a few square kilometres. Other areas of single, low impact, low sensitivity use (such as dispersed agricultural use) may be extensive over several similar groundwater response units.

The hydrogeologist's role will be to aid the decision makers' interpretation of the importance, vulnerability and present status of groundwater resources. The key decision will be whether to maintain the current status and protect resources from further impacts, or to try and improve the quality of the groundwater resource. At a comprehensive level, it is expected that scenarios will need to be developed and numerically modelled in order to assess the implications of setting a higher class. At all levels the consequences of Classification need to be communicated.

DWAF has a strong history of managing direct impacts on surface water resources such as discharge of effluent to rivers and stream reduction activities. The impacts of many land-based activities on groundwater resource quality are often less well understood and controlled. For instance construction in recharge areas (recharge reduction activities), petrochemical pipelines, industrial manufacture. The exceptions are the impacts of waste sites and mining. Any attempt to improve the quality of groundwater resources will require strong preventative and remedial action on the part of DWAF in partnership with local government and land-use planners. The costs and effectiveness of these management actions will take many years to become apparent, understanding the **achievability** of improved classes will be speculative for some time to come.

During this phase a risk assessment may be necessary to correlate the understanding of the intrinsic vulnerability of the resource to contamination and over-exploitation, and the potential or current hazards to resource quality in the area. Groundwater risk assessment can be defined as the probability of an adverse effect or effects on the quantity and/or quality of groundwater associated with measured or predicted hazards (Dennis *et al*, 2001).

Checklist

- Which are the most important groundwater management units?
- Where are important areas most vulnerable?
- What are the current hazards to groundwater resources in the area?
- What are the implications of preventing degradation groundwater resources in terms of groundwater use and land-based activities?
- What are the implications (and costs) of improving and remediating the quality of groundwater resources?
- Are the stakeholders prepared to accept the costs and benefits of protecting/ improving groundwater resources in certain groundwater management units?

3.15.3 Rules, tools and outcomes

RULE

Delineate the final management units based on:

- **Current and future requirements for groundwater use.**
- **Vulnerability**
- **Common actions necessary to manage groundwater for desired levels of use.**

→ ***Outcome***

Areas for which a single management class and a single set of RQOs are necessary.

RULE

Describe scenarios of management goals and actions for each management unit and the consequences of assigning likely management Classes for

- **All current groundwater uses.**
- **Potential and natural groundwater uses.**
- **Land-care management**
- **Economic development**

→ ***Outcome***

Information for the decision process on the consequences of Classification which are understandable to stakeholders in the area.

The overall outcome for this step for all levels of determination should be a GIS based database with the layers of information described above. Higher levels of determination will give higher levels of confidence and greater degrees of resolution in the data layers. In comprehensive determinations, numerical model outcomes may be linked to some GIS layers.

3.16 Limits to the Classification of groundwater

Implementation of the Classification system should enable protection of groundwater resources appropriate to their importance (use) and vulnerability. It is important to note that the system is limited to this is not intended to enable all aspects of integrated groundwater management. Implementation of the Class, Reserve and RQOs, for instance, will not necessarily tell water managers how much groundwater is available to be allocated. The impacts of individual license applications should be assessed in the context of the Class of effected resources before approval is given.

The Classification system and the RDM are one of several sets of measures outlined in the NWA, which when implemented together will ensure sustainable, equitable, efficient, optimal use of South Africa's water resources.

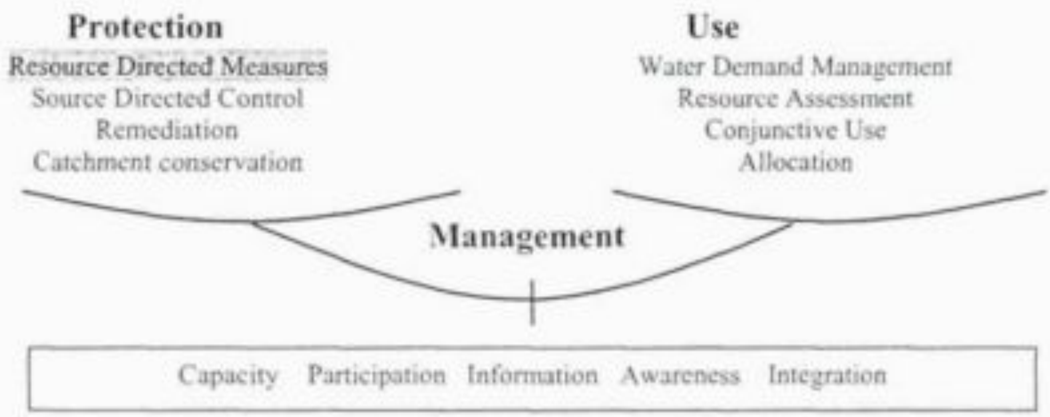

Figure 3.9. Concepts of IWRM for South Africa (DWAF, 2002b).

3.17 Recommendations

The guidelines presented in this document wil need to be widely reviewed and approved prior to the finalisation of the methodologies for all water resources in 2004. The WRC and DWAF should work together to ensure that this happens timeously.

Each classification process should incorporate peer preview and review of the work, including the outputs, assumptions and confidence. Implementation should also be reviewed by the National DWAF RDM office to ensure continuity and to ensure that the principles of the methodology are being adhered to. DWAF needs to establish clearly how peer review will be incorporated into the implementation of RDM and start practicing this.

One of the most important tools needed to support the Classification process is the establishment of a standard approach to determine groundwater vulnerability to contamination in fractured rock terrains. It is recommended that this area should receive attention (from the WRC). Vulnerability to over-exploitation also needs a more quantitative standard assessment procedure for South African conditions.

The data needs of catchment management agencies, water management area agencies and the department as a whole need to be taken forward at the highest level to other data providing agencies, such as Council for Geoscience, ARC, and the Surveyor General.

It is suggested that the department negotiate with the custodians of current essential datasets for them to add relevant value. This could be as extensive as the inclusion of additional hydrogeologically related data in attribute tables to full spatial analyses.

The custodians/ agencies in question could charge for these services and the department could ensure that all of the parties using the data, including themselves, were using standardised data. One key example of this is the South African Weather Bureau (SAWB). If specific climatic parameters and data are required, SAWB could offer a value added service that would cater directly for the geohydrologist's needs.

It is common thinking in the spatial technologies communities that domain specific agencies should be 'custodians' of their data only. As newer technologies become available and bandwidth improves it will be possible for data users to use data directly from an agency's server without maintaining local 'copies' of data except their own domain specific data holdings.

A more forwarding thinking approach to the National Groundwater Database (NGDB) or ReGIS needs to be implemented. Metadata needs to be available on the Internet and a browsing and self help data selection and download system would be a logical step forward for this valuable resource

It is widely recognised that GIS is firmly entwined in the future of groundwater classification, management and exploration. If this is to be the case, data must be managed with this in mind. The Geomatics department and spatial data provision departments of other government agencies must put in place polices to ensure that their investments in data not wasted or lost. Metadata collection and dissemination systems /programmes must be implemented.

The Water Research Commission should re-examine the standard format for project outputs and develop methods for ensuring data associated with WRC projects is provided as part of the deliverables and in standard formats. Once these policies are in place the data needs to be managed and made available to the scientific community through both Internet map services and for download.

4. Interaction with Surface Water Bodies

As hydrogeologists, we tend to be familiar with the analysis of surface water flow in order to understand the mechanisms of recharge. However the scope of interaction between surface water bodies and groundwater is broadened by introduction of the Ecological Reserve determination to include analysis of exchange of water between the two (especially floodplain and stream channel). Consequently hydrogeologists in South Africa have become increasingly involved with stream ecologists and riparian habitat groups who attempt to determine aquatic ecological Reserve (Xu et al. 2000).

One of the critical concepts that is key to understanding the interaction between groundwater and surface water is the definition of groundwater recharge. In this document, recharge is defined as the amount of water, including rainfall, which is added to groundwater table in the saturated zone. Infiltrating rainfall water that could not reach saturated zone before discharging into surface water may be called interflow. This implies that a river hydrograph may have three components: direct runoff, interflow through the unsaturated zone and groundwater discharge from the saturated zone. Although a baseflow is often defined as the groundwater discharge from the saturated zone in classic hydrogeological text books (Freeze and Cherry, 1979; Domenico and Schwartz, 1990), the word "baseflow" is generally known to many hydrologists as delayed flow components (mainly groundwater), as opposed to a quick, direct runoff (Singh, 1988). Thus baseflow itself is not indicative of origins of water sources. The baseflow is normally separated by removing the direct runoff from a hydrograph (Domenico and Schwartz, 1990). As a result, such a baseflow component may still contain some interflow component. Therefore identification of the interflow component and subtraction of it from separated baseflow is prerequisite for quantification of groundwater contribution to streams.

This chapter is focused on origins of baseflow generation processes from a view point of hydrogeomorphology. Typical scenarios of groundwater contributions to streams are discussed under generalised hydrogeological settings. Together with good knowledge of site - specific problems, traditional hydrograph-separation techniques to be applied under the proposed hydrogeomorphologic framework would help to achieve quantification of groundwater contribution to the stream.

4.1 Previous work

4.1.1 Stream Classification

The possible relationships between river and groundwater are outlined below (Table 4.1).

Table 4.1: Relationship between surface water (SW) and groundwater (GW) (adapted from Vegter, 1997).

Parameters	Effluent	Intermittent	Famished	Influent	Detached	Alternately In/Effluent
Temporal	All year	Period after recharge	All year	All year	All year	Alternately
Spatial or flow direction	GW to SW	GW to SW	No Exchanged	SW to GW	SW to GW, separated	GW to SW/SW to GW
Characteristics	Perennial	Intermittent	Perennial/ Ephemeral	Perennial	Perennial/ Ephemeral	Perennial

It must be pointed out, however, that Vegter's approach failed to take into account the geomorphologic framework under which hydrogeological settings may be conceptualised.

4.1.2 Hydrograph-separation Techniques

It is always useful to apply hydrograph-separation techniques for comparison with results obtained using a hydrogeological approach, even though baseflow may not be entirely from groundwater. The hydrograph-separation methods considered are introduced as follows.

4.1.2.1 Chemical method

This method is widely applied by hydrogeologists. It would apply to any conservative constituents like Chloride. The formula is presented as follows (Freeze and Cherry, 1979):

$$Q_g = Q_T \cdot ((C_r - C_d)/(C_g - C_d)) \quad 4.1$$

Where Q_g is groundwater contribution. Q_T is the total streamflow. C_d, C_g and C_d are chemical concentrations for direct runoff, river and groundwater, respectively. Eq. (4.1) makes use of groundwater concentration C_g, direct runoff (or rain water) concentration C_d and stream concentration C_r.

4.1.2.2 Herold method

This method developed by Herold (1980) is based on the following equation:

$$Q_{gi} = Q_{gi-1} \cdot Decay + Q_{i-1} \cdot PG \quad 4.2$$

where Q_g is groundwater contribution. Q_{i-1} is the total streamflow with the subscripts *i* and *i-1* refer to the current and preceding month. *Decay* is groundwater factor (*0<Decay<1*), while *PG* is groundwater growth factor (%). Eq. (4.2) shows that the current groundwater component Q_g represents the combined effect of previous groundwater after decay (Q_{gi-1}*$Decay$) and rainfall induced recharge (Q_{i-1}*PG).

Having been tested by Pitman and Vegter using flows measured at the Department of Water Affairs and Forestry's gauge No X3H001 on the Sabie River, the method was consequently adopted in the Water Resources 1990 project, in which a time series of monthly flows were separated into surface and groundwater components for each of the approximately 2000 Quaternary catchments of the study area (South Africa, Lesotho and Swaziland).

4.1.2.3 Smakhtin method

Based on Nathan and McMahon (1990), Smakhtin (2001) proposed a formula calculating surface runoff. Groundwater contribution is the total flow minus quick surface runoff.

$$Q_{ti} = Q_{ti-1} \cdot filter + 0.5 \cdot (1 + filter) \cdot (Q_{Ti} - Q_{Ti-1}) \quad 4.3$$

where the filter is about a value varying from 0.95 to 0.99. However it is noticed that selection of the initial value of baseflow would influence separated values.

By comparison, the Herold method is theoretically most meaningful. It is capable of dealing with a variety of interactions if a good combination of parameters (*Decay* and *PG*) is used.

4.2 Geomorphologic Classification of Streams

A stream may be classified based on various criteria for various purposes. For a hydrogeological investigation, it is important to characterize a stream in terms of its geomorphologic features. According to Partridge (Per. Comm, 2001; Xu *et al.* 2001), the following generalisation may be recognized.

- Upper catchment areas
  - Steep profiles
  - Deep incision
  - Inflow from valley sides in humid areas
  - Large bedloads
- Middle courses
  - Bedload deposition
  - Braided channels near mountains
  - Neotectonic uplift creates incision convex profile lower down with riffle and pool configuration
  - A few meandering types in stable areas (e.g. Klip)
- Lower courses

- Neotectonic uplift causes incision, esp. of old meanders
- In the arid west, rivers are exotic, with deeper bed deposits and thicker terraces
- In estuaries, sea level drawdown results in deep infills with some saline intrusion
- Meanders on wide coastal plains (e.g. Pongola)

- Special cases of endoreic drainage into large pans, the Kalahari etc (e.g. Okavango rivers)

The above geomorphologic descriptions provides hydrogeologists with information that is related to not only the type of groundwater and surface water relationships being dealt with but also the kind of aquifer boundary conditions that should be taken into account when conceptualising groundwater flow systems. In general, the implications of groundwater interaction with streams (rivers) may be summarized as follows.

- Upper catchment areas

Type a: Streams without bank storage (like a braided river). This type is most likely to occur in mountainous areas. Stream flow possesses the energy to incise stream channels, resulting in deep cliffs on either side. At a local scale, subsurface stormflow (or interflow) could seep out into the stream. However, at a regional scale this is the recharge area for regional groundwater system.

- Middle courses

Whatever occurs in upper catchment areas may still exist here. At a regional scale this is the groundwater runoff area, and at a local scale the direction of interaction between groundwater and the river may be changeable.

Type b: Streams controlled by bed morphology (e.g. the pool, riffle). This type is often associated with, but not restricted to Type a. Although interaction with groundwater due to bed morphology alone is very localized, interaction with groundwater at a regional scale can be very significant. For the aquifer system, It could be of a recharge or discharge area.

- Lower courses

Type c: Streams with bank storage (e.g. a meandering river). This type often appears in topographically flat areas, near a regional base level. Stream flow may result in development of horizontal terrain, which may become the bank storage buffer for groundwater. Generally, this is the discharge area for the regional groundwater system. However, it should be noted that because of plateau upliftment in South Africa, few meandering rivers are evident.

Type d: Streams influenced by channel morphology. This type is often associated with, but not restricted to Type c. Interaction with groundwater due to channel morphology occurs on an intermediate scale. It is often of a discharge nature, for the regional groundwater system.

- Special cases

Type e: Streams dictated by geological structures, especially neotectonic movements where applicable. Here the occurrence and interaction with groundwater is site specific.

Type f: Streams with headwater originating from an allogenic source (e.g. Molopo River). Since this type does not possess much energy to alter the stream channel itself, it would occur more frequently in ephemeral streams in the drier, western parts of the country. The aquifers could be recharged with the occurrence of a big flood.

Note: The role of bank storage is significant only if it is composed of unconsolidated sediments with a good storage coefficient. The advantage of this kind of classification seems that each type could be associated with a particular geomorphologic and hydrogeological setting, including flow boundary conditions, and its ecological inference.

4.3 Types of interactions and their characteristics

From hydrogeomorphologic point of view, four types of interactions between streams and groundwater can be recognised. Let us begin with a general case for purpose of understanding of terminology used.

4.3.1 Single peak flow

A single peak flow is illustrated in Fig 4.1. Hydrograph-separation method involves the following terms:

1. Hydrograph: flow changes over time.
2. Hydrograph-separation: used to divide hydrograph into two parts: quick runoff and slow flow (mainly groundwater component), the latter is controlled by hydrogeological conditions upstream.
3. Hydrogeologic Technique: hydrogeomorphologic typing
4. Parameter T (d) can be determined based on existing methods (Domenico and Schwartz, 1990; Rorabaugh ,1964; and Linsley *et al.*, 1958)
5. Point A: starting of baseflow recession, point B: recession point at peak flow and point C: quick runoff terminated after T time.

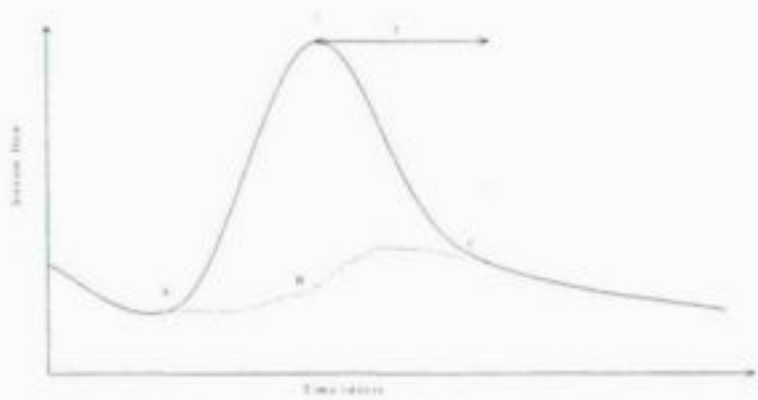

Figure 4.1: A single peak flow.

4.3.2 A rule of thumb

There are still many difficulties regarding how to accurately separate groundwater discharge from hydrographs. For instance, monthly time scale is normally used rather than a daily scale for the separation. However, a rule of thumb may be proposed to assist with the separation process. Following four types of interactions between streams and groundwater can be recognised.

4.3.2.1 Type 1: Losing or gaining streams

This type may occur in the upper catchment where regional groundwater level is constantly below the stream stage as shown in Fig 4.2 (1a). It may also be found in places where permeabilities of stream bed materials are such that amount of losing water from streams is somewhat limited. Constant gaining streams may also exist when streams are fed by groundwater from confined aquifers (case 1b of Fig 4.2).

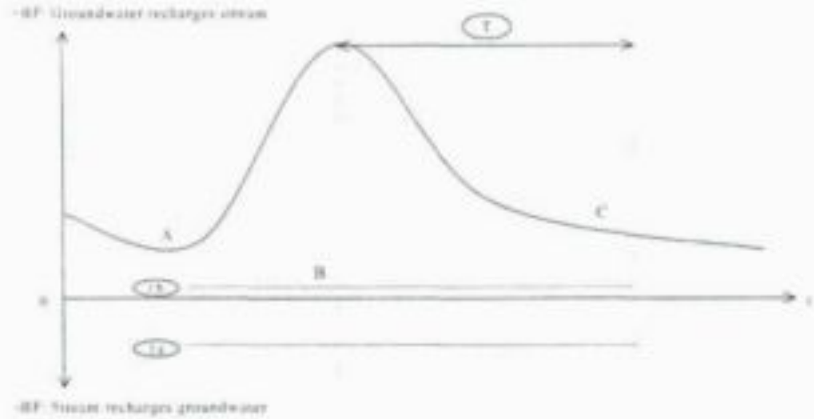

Figure 4.2: Type 1.

4.3.2.2 Type 2: Intermittent streams

This type may be found in the middle course where groundwater recharges river during dry period while river recharges groundwater during floods. The baseflow component would have a cutoff under the peak flow time as in Fig 4.3.

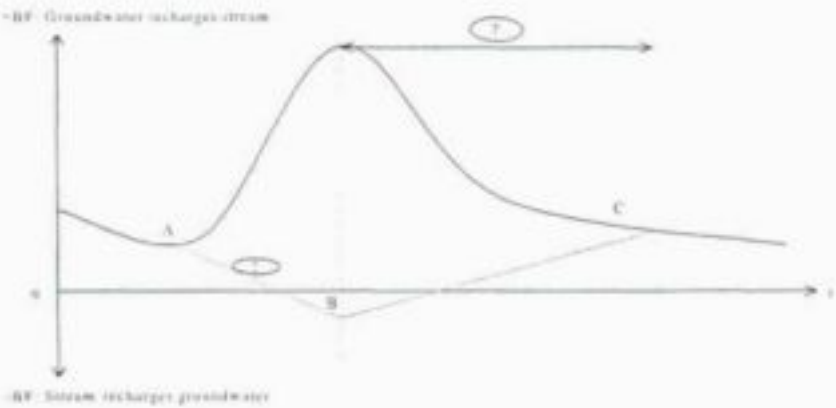

Figure 4.3: Type 2.

4.3.2.3 Type 3: Gaining streams with or without storage

This type is often observed in the lower course where groundwater level may be constantly higher than river stage. Baseflow component would increase in either S curve or a straight line, depending on presence of bank storage. As shown in Fig 4.4, three cases are: 3a for porous media without bank storage, 3b for fractured media without bank storage and 3c for with storage.

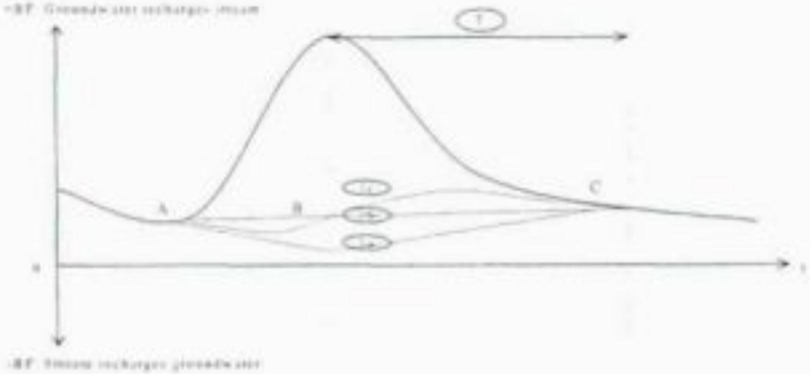

Figure 4.4: Type 3.

4.3.2.4 Type 4: Interflow dominant streams

This type may occur in the upper catchment where interflow may be dominant component of stream hydrographs. If regional groundwater level is below the stream stage, traditional separation techniques would give indication of magnitude of interflow contribution. It may also be complicated by geological structures, as cases may be. As shown in Fig 4.5, the baseflow displays similarities to the quick runoff in terms of their phase and amplitude.

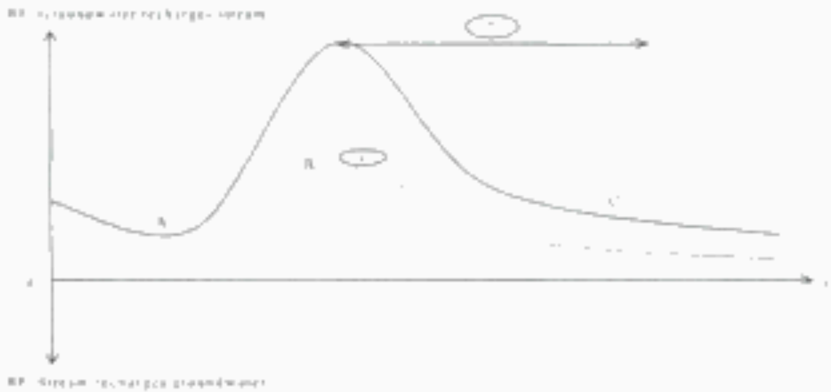

Figure 4.5: Type 4.

4.3.3 Summary

In terms of hydraulic connection, the above types of interactions between streams and groundwater can be summarized as follows (Fig 4.6, Table 4.2).

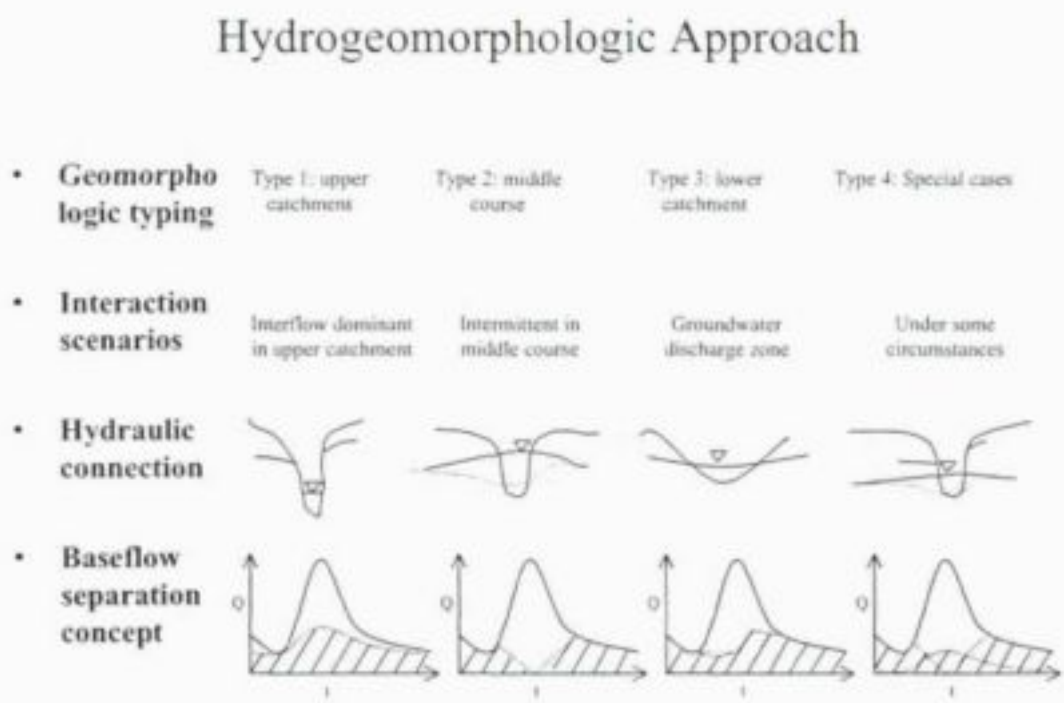

Figure 4.6: An illustration of the different relationship between rivers and groundwater.

Table 4.2 Types of Interaction between Groundwater and Rivers

Type	ıre of Interaction	Geomorphologic Type	Significance of E Reserve	Example (Vegter and Pitman, 1996)
1	Influent streams (losing stream)	a	No	Section of Kuruman and Molopo Rivers
2	termittent streams	b	Yes	Upper reaches of the Salt River
3	Effluent streams (gaining stream)	c, d, e	Yes	Molopo and Kuruman Eyes
4	connected streams	f	No	In the arid north western parts of country

4.4 Groundwater Flow Process

For the purpose of quantification of the groundwater component of the ecological Reserve, we have focused on a gaining stream. Suppose that the groundwater outflow to the stream is driven by rainfall recharge, and that the aquifer is bound by no flow conditions along the surface water catchment limit. This is a one-dimensional unconfined flow bounded by no-flow on one side, and a stream on another side. Fig 4.7 sketches out the flow model where $N(t)$ is rainfall recharge; h is water elevation and x is distance; P_i is an imaged water particle with its representative flow component as g_i; Q_e is groundwater discharge.

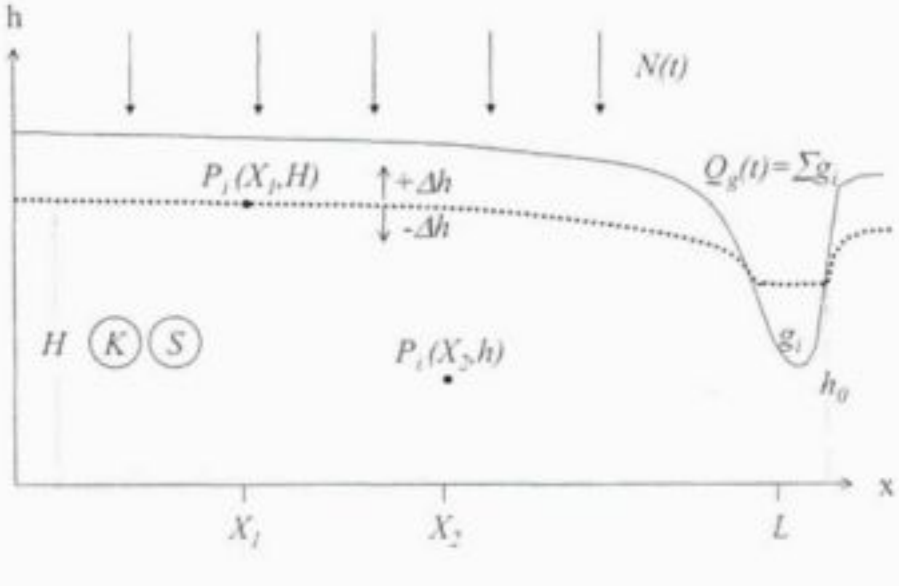

Figure 4.7: Flow model of a one-dimentional aquifer with recharge from rainfall and odischarge towards a river.

Figure 4.7 depicts a generic situation simplifying natural conditions. Ignoring the transient nature of water level fluctuation, Darcy's law may be applied to averaged flow condition. As a result, the aquifer outflow may be characterized by aveage groundwater gradient towards the stream as in Eq. (4.4).

$$(H - h_0) = NL^2/2T \quad (4.4)$$

Eq. (4.4) shows that the groundwater mounting above a river or stream is largely controlled by the distance from a stream to catchment border, and is partially reciprocal of aquifer transmissivity $T=KH$.

Relationship of recharge events, water levels and discharges is hydraulically correlated. But due to possible geometric locations of a borehole or wellfield within an aquifer, the relationship among recharge events, water level fluctuations and discharges may have two different cases as illustrated as Figure 4.8.

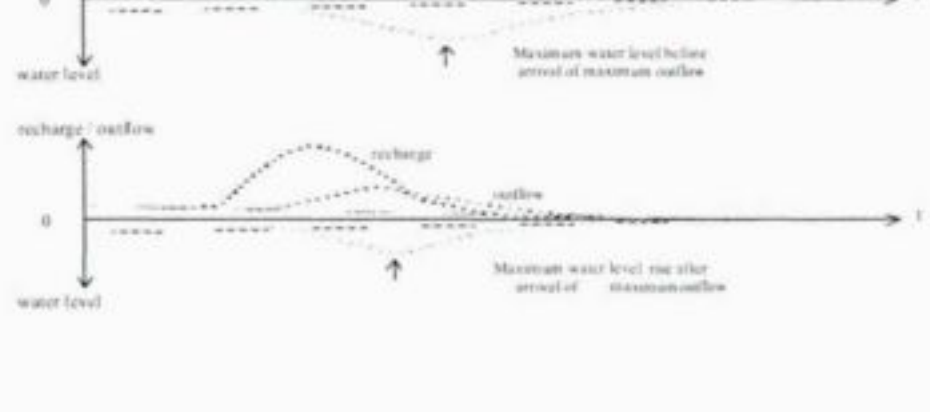

Figure 4.8: Relationship among recharge, discharge and water levels.

4.5 Generation of Discharge Time Series

For generation of groundwater discharge time series, one may make use of baseflow series proposed by Vegter and Pitman (1996). A baseflow series may also be estimated from SARES program (Hughes, 2000). In addition, the following approaches should be adopted.

4.5.1 Using hydrographs

Baseflow Program is available at the site: http://www.science.uwc.ac.za/earthscience/index.htm. An example is shown in Figure 4.9. Out of three methods discussed in Section 4.1.2, the chemical separation method is perhaps the most practical technique that allows for the use of chemical data readily available for some period of time. At least the results of this method can be used as calibration points for other methods.

The Chemix method in Baseflow program also available at the site: http://www.science.uwc.ac.za/earthscience/index.htm is such a hybrid of hydrogeochemical method and other techniques.

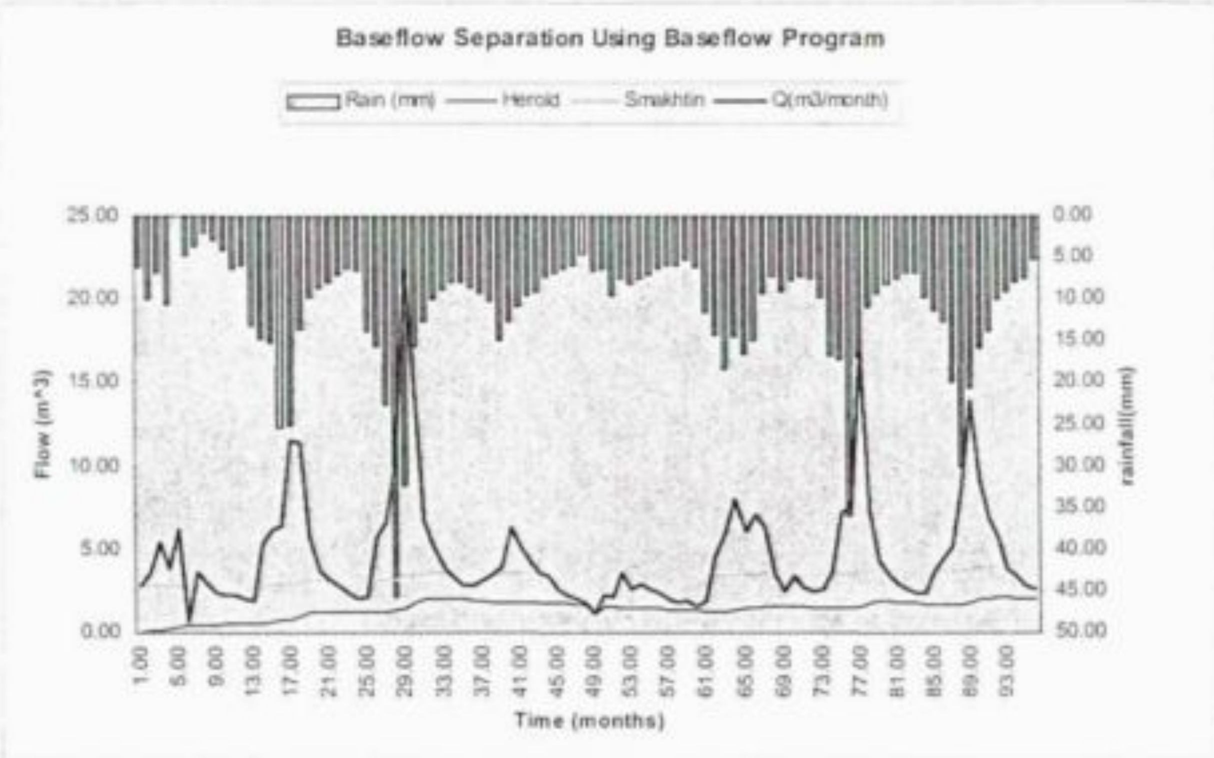

Figure 4.9: An example of hydrograph-separation using Baseflow Program.

4.5.2 Hydrogeomorphologic approach

Hydrogeomorphologic approach to quantification of groundwater contribution allows qualitative knowledge of field problems to be incorporated into hydrograph analyses. Before proposing some rules to follow, we can suggest that the groundwater contribution to baseflow be summation of decay of previous groundwater contribution ($Q_{gi-1}*D$) and rainfall induced flow increment ($Q_{i-1}*I$). Eq. 4.2 may be modified and rewritten as

$$\begin{aligned} Q_{gi} &= Q_{gi-1} \cdot D + Q_{i-1} \cdot I \\ &= \left(Q_{gi-2} \cdot D + Q_{i-2} \cdot I\right) \cdot D + Q_{i-1} \cdot I \\ &= Q_{g0} \cdot D^{i} + Q_{0} \cdot I \cdot D^{i-1} + \ldots Q_{i-j} \cdot I \cdot D^{i-j} \ldots + Q_{i-2} \cdot I \cdot D + Q_{i-1} \cdot I \end{aligned} \qquad 4.5$$

Eq. 4.5 indicates that baseflow Q_{gi} is a function of Q_i and Q_{g0} (an initial groundwater contribution that can be estimated using a method proposed in Section 5.3.2.2) with parameters I ($-1 \sim 1$), D ($0 \sim 1$) and where $l < j < i$. Different range of these values can be specified under different types of groundwater and surface water interactions as discussed in Section 4.3. Following rules are proposed in Table 4.3 when a use of Eq. 4.5 is made.

Table 4.3: Types of Interactions and Range of Parameters.

Type	ure of Interaction	Geomorphologic Type	Q_{g0}	D	I
1	Influent streams (constant losing streams)	a	-	1	0
2	Intermittent streams	b	+, -	+	-
3	Constant gaining streams, WL > stage (with storage)	c, d, e	+, + (+)	1, + (<)	0, 0.50 ~ 1 (0.01 ~ 0.50)
4	iterflow streams	a, f	0	0 ~ 0.5	+

Further more, use of algorithm for the estimation of groundwater discharge is proposed for Types c, d and e. It is assumed that the flow model is a one-dimensional aquifer with recharge from rainfall and outflow towards the stream.

A generic procedure, proposed as shown in Fig. 4.10, is explained as follows:

1) Conduct a field visit and collect information on borehole water level, etc.
2) Establish the interaction relation between groundwater and surface water bodies. This entails identification of the interactive Types.
3) Estimate recharge by using available methods, e.g. CRD method (Bredenkamp *et al.*, 1995; Xu and Van Tonder, 2001).
4) Compile a water table contour map or generate a contour map for a steady state using numeric model. Using numeric model generates value of Q_{g0}.
5) Apply Excel program to achieve reasonable quantification of groundwater discharge to streams. The calibration can be done through comparison with known recharge figure.

Assess whether or not instream flow requirement is met by taking into account possible abstraction. At present a spreadsheet program is being developed under this project. The groundwater discharge time series, calculated using a numeric model, is generated by using the spreadsheet program. It must be pointed out that the proposed method is still to be tested using case studies.

4.5.3 Numerical Approach

In many cases, numerical modelling has to be adopted to account for complicated hydrogeological settings. More discussion will be given when dealing with quantification of the Reserve.

4.5.4 Discussion

Interflow is observed as an important mechanism that may account for part of baseflow. Such flow may occur under the following circumstances:

- Soil horizons may act as flow barriers, which hinder a direct downward percolation of precipitation.
- A partially saturated flow may be formed via a perched water table.
- In peaty soils a special type of interflow (called piping) occurs along preferential flowpaths.
- Favourable geometric configuration of fractured networks may lead to the formulation of interflow towards the river.

On the other hand, isotope analyses indicate that contribution of groundwater to peak flow may be up to 70% in some cases according to Verhagen (Per. Comm., 2001). Mechanisms of generation of this rapid saturated flow are complicated. The following cases may be appealing to hydrogeologists:

- Due to very low storativity, a rapid increase in the regional hydraulic head caused by rainfall reaches the surface. At same time, rain flows as surface runoff towards the river and contributes to the runoff peak.
- The water table in the recharge area quickly rises up due to the percolation of rainwater. Hydraulically confined or semi-confined water in fractured systems is pushed out of the aquifer beneath the riverbed through a piston flow mechanism.

If this method is to be applied, attention should be paid to the following points.

- The relationship between groundwater and stream stage must be established. They should be representative for area of interest.
- It is assumed that the recharge is spatially uniform, with the lumped parameter approach being taken.
- Significance of isotope methods should be checked out if possible.

Accurate calculation of groundwater contribution to stream at a meaningful resolution is very difficult. Many aspects should be taken into account. These include factors like agricultural development (irrigation), urban and industrial development, and modifications to river valleys. The proposed hydrogeomorphologic approach still needs verification in real case studies. However its use in combination with established hydrograph-separation techniques appears to provide a good conceptual framework where time-series of groundwater discharge to streams may be estimated with reasonable accuracy in order of magnitudes. A number of investigations need to be undertaken to refine the methodology.

4.6 Conclusion

The instream flow requirements (IFRs), only expressed as time series, present dynamic conditions that are derived to protect aquatic ecosystems, an approach to quantification of groundwater contribution to IFRs should be compatible with that of IFR time series. It is recommended that Baseflow Program be used to estimate monthly groundwater discharge time series initially (Table 4.4). A suit of techniques ranging from simple Darcy's law to complicated numerical modelling could be further employed, depending upon availability of data and the level of RDM determination.

Table 4.4: Summary of Hydrograph-separation Techniques of Baseflow Program.

Techniques	Data required	Parameters	Comment	Confidence for Ecol. Reserve
Herold method	Rainfall; Stream flow; Abstraction	Decay; PG	Subjective & multi-choices	Low to high
Smakhtin method	Rainfall; Stream flow; Abstraction	A filter constant	Subjective but easy	Low to medium
Chemix	Rainfall; Stream flow; Abstraction; Chemical concentration for groundwater, runoff & stream flow	Separated baseflow to be calibrated by chemistry data	Separated baseflow may be calibrated by chemistry data	Medium to high
Hydrogeomorphologic approach	Rainfall; stream flow; water level; recharge; T & S; other geometry	Aquifer parameters	Under development; physically meaningful	Low to high

5. Setting of the Reserve

5.1 General

The Reserve is a generic term representing both basic human needs and flow requirements for aquatic ecosystems. In the case of rivers, it is referred to as Instream Flow Requirements (IFRs), for wetlands, it may be called Wetland Flow Requirements, and for estuaries, it is called Estuarine Flow Requirements.

Once the future management class has been chosen, the quantification of the Reserve must be determined. Typically different Reserve scenarios representing different levels of protection will be determined to inform the decision of which class to set.

The requirement for the quantification of the Reserve involves a review of previous Steps of the generic procedures and linkage to other groups from surface hydrological and ecological disciplines.

IFRs are often expressed in terms of high flow, low flow and drought flow requirements for the hydrological year starting from October to next September. The fundamental assumption for the derivation of the IFRs is that rivers with a high degree of hydrological variability will require a lower proportion of their natural mean annual runoff, because they are accustomed to experiencing such conditions.

5.2 Preparation

The objective of this step is to translate information gathered previously into technical terms that can be implemented in Reserve quantification. Objective functions should be established for the simulations to satisfy the Basic Human Needs and Ecological Reserve at selected management classes for that groundwater management unit.

5.2.1 Data availability

At this stage it is important to assess data availability, which in turn influences the selection of methods for the Reserve quantification. Some important data sources are listed in Table 5.1 and Table 5.2.

Table 5.1: Summary of the data sources.

Data Type	Sources
Geology • Borehole logs	National Groundwater Data Base (NGDB), Council for Geoscience
Geohydrological information • Borehole location and observed groundwater level • Aquifer property • Existing abstraction • Groundwater Recharge (Table 5.3)	NGDB, Field Data, National Groundwater Maps (Vegter, 1995);
Ecological information • Ecological constraints	Ecologists /Surface water hydrologists (DWAF)
Other data • Population depending on groundwater	Surveyor General, Field data

Table 5.2 Additional data sources.

Data Type	Sources
Geology • Lithological characteristics • Structures	National Groundwater Data Base (NGDB), Field data, Council for Geoscience, National groundwater maps (Vegter, 1995)
Geohydrological information • Existing groundwater models • Groundwater quality • Geohydrological maps	NGDB, WMS, Field data, National groundwater maps (Vegter, 1995)
Hydrological information • Surface water bodies • Surface water levels • Gauging station records • Rainfall & evaporation	Surface water hydrologists (DWAF), Field data, WR90 – rainfall (Midgley *et al.* 1994), National groundwater maps – baseflow (Vegter, 1995)
Other data • Land cover/Land use • Topography	Field data, CSIR - ARC, Surveyor General

5.2.2 Understanding of the Ecological Reserve

Ecosystems are dependent on natural flow variability. If the flow is constant, problems can be expected (e.g. sensitive species are dominated by new pest species, like the "black fly" problem in the Eastern Cape). During the wet season fish have different requirements as opposed to that during the dry season (e.g.

breeding period). For this reason, the Reserve, IFRs in the case of rivers, does not refer to only volume but also to duration, frequency and timing. One of the critical issues for the assignment of an annual IFRs value into monthly IFRs values, is how to evaluate groundwater contribution to baseflow. A hydrogeologist involved in the Reserve study must investigate and establish the relationship between groundwater and surface water bodies in order to fully understand hydrogeological implications of the IFRs.

5.3 Quantification of the groundwater component of the Reserve

The objective of this step is to determine the quantity and quality of water required to satisfy the Basic Human Needs and Ecological Reserve at the selected management class for that groundwater resource.

5.3.1 Water balance

The water balance model, also referred to as the water budget, mass balance or black box model, was developed in the 1940's by Thornthwaite (1948) and revised by Thornthwaite and Mather (1955). A water balance model is a quantitative evaluation of water gained or lost from the groundwater system under investigation during a specific period of time. It is assumed that the change in groundwater stored in the system relates directly to the change in the groundwater level within the system, and it can be expressed as:

$$\text{Change in Storage} = \text{Inflow} - \text{Outflow} \quad (5.1)$$

For the groundwater system shown in Figure 3.1, equation 5.1 may be written in the form of water balance terms:

$$\frac{\Delta Q_S}{\Delta t} = \pm Q_N \pm Q_R \pm Q_B \pm Q_L \pm Q_W \quad (5.2)$$

where

ΔQ_S [L^3] = change in storage volume within the time increment Δt

••Q_N [L^3/T] = natural groundwater recharge or discharge rate

••Q_R [L^3/T] = leakage rate from/to surface water bodies

••Q_B [L^3/T] = subsurface flow rate from/to horizontal adjacent aquifers

••Q_L [L^3/T] = leakage rate from/to vertical adjacent aquifers

••Q_W [L^3/T] = local infiltration or abstraction rate, e.g. wells

Δt [T] = time increment

Under the steady-state groundwater flow condition, the change in storage is zero, and the equation can be rewritten as:

$$\pm Q_N \pm Q_R \pm Q_B \pm Q_L \pm Q_W = 0 \quad (5.3)$$

Estimation of the groundwater component of Reserve discussed in the following section is based on the assumption that the groundwater flow system is under the steady-state condition.

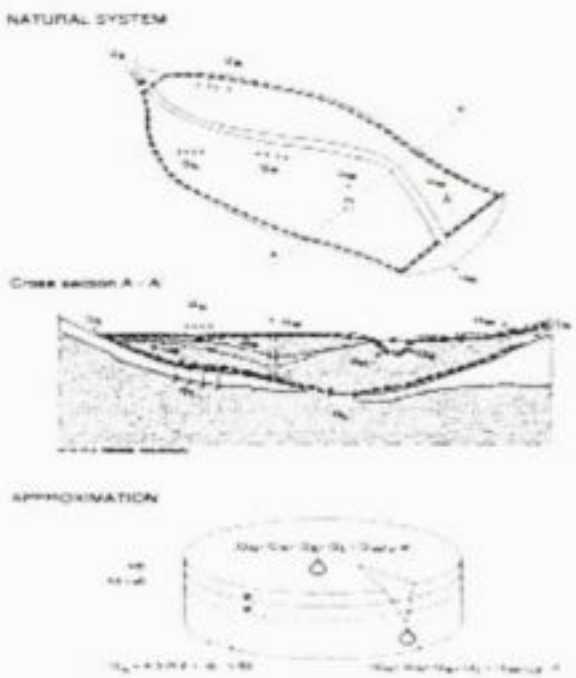

Figure 5.1: Water balance model for a groundwater flow system (after Spitz and Moreno, 1996).

5.3.2 Calculation of the water balance terms

5.3.2.1 Estimation of Natural Groundwater Recharge and Discharge

Groundwater recharge due to precipitation, or discharge due to evaporation and transpiration is generally the most prominent element in the water balance calculation. They are influenced by many factors, such as precipitation intensity, the depth of the groundwater level, soil type, climate condition, vegetation, slope of the ground surface, etc. Because of the unidentified nature of these factors, an accurate estimation of natural groundwater recharge and discharge is very difficult.

The EXCEL-Spreadsheet RECHARGE (Van Tonder and Xu, 1999) is used to determine the groundwater recharge. RECHARGE features a user-friendly interface. It is capable of using different methods including the Chloride method, Saturated Volume Fluctuation method (Van Tonder, 1989), Cumulative Rainfall Departure method (CRD) (Wenzel, 1936; Temperley, 1980; Bredenkamp *et al.*, 1995), isotopes method, and a series of qualified guess methods. A new CRD method, which is able to accommodate short rainfall data, can also be used (Xu and Van Tonder, 2001). The data required by each method are listed in Table 5.3.

Table 5.3: Data required by the RECHARGE program.

Methods		Data Requirement
Chloride method		• Average chloride concentration in groundwater and rainfall • Average annual rainfall
Saturated Volume Fluctuation (SVF) method		• Monthly abstraction from aquifer • Lateral inflow and outflow • Monthly water level
Cumulative Rainfall Departure (CRD) method		• Lateral inflow and outflow • Monthly abstraction from aquifer • Monthly water level • Monthly precipitation
Qualified Guess	Soil and vegetation information	• Percentage coverage of area with soil material (% clay content) • Percentage coverage of area with woods/trees, grasslands and bare soil
	Geology	Type of soil covering the ground surface
	Vegter	Vegter's map (WRC and DWAF, 1995)
	ACRU	ACRU map (Roland Schulze) (WRC and DWAF, 1995)
	Harvest potential	Harvest Potential Map (DWAF, 1996; Baron *et al.* 1998)
	Base flow	Groundwater Component of River Base Flow Map (WRC and DWAF, 1995)
Isotopes (Residence time)		• $^{2}\delta$ values in (un) saturated zone • ^{18}O values

5.3.2.2 Estimation of the Water Exchange with Surface Water Bodies

Based on previous discussion in Chapter 4, surface water bodies (rivers, lakes, channels, streams, etc.) may gain water from aquifers or lose water into groundwater systems, and the exchange rate of water is usually controlled by the difference in the hydraulic heads (water levels) and the resistance of the media between the groundwater and surface water bodies. Four types of the interactions are discussed in Table 4.2 and Table 4.3. But only three types are differentiated based on hydraulic connections.

- Influent: The groundwater level is lower than the surface water level.
- Effluent: The groundwater level is higher than surface water level, groundwater always recharges surface water.
- Intermittent: The groundwater level is higher than the bed of the surface water body, but depending on the elevation of the water level, the groundwater may recharge the surface water body or the surface water recharge the groundwater.

This leakage principle is usually used to calculate the leakage rate from or to surface water bodies. This approach is, however, not always practical for the rapid and intermediate level estimation of the groundwater component of Reserve, because all factors in the equations of section 2.2.2.2 (Zhang, 2000) vary with time and position, and their use often requires considerable efforts with regard to parameter estimation. Another approach, which uses the numerical model PMWIN (Chiang and Kinzelbach, 1998) as a computational tool, is suggested below:

1). Discretize the study area:

The study area is subdivided into finite-difference blocks, the size of the blocks depend on the size of the study area and the desired resolution.

2). Assign the measured groundwater level into each block:

Generally, the observed water levels are only available at some discrete points, and an interpolation method must be used to obtain the water levels for all finite-difference blocks within the study area. If the groundwater levels are well correlated with the topography, the interpolation program TRIPOL (Van Tonder *et al.*, 1996) is a better choice. Otherwise, interpolation methods such as Inverse Distance (Shepard, 1968) or Kriging can be used.

3). Assign transmissivity values or hydraulic conductivity values and aquifer thickness to each block.

4). Assign a high storage value to each block:

When a high storage value, say 1.0, is used, the water level of each block will only change very slightly during a flow "simulation". This ensures that the measured water level will be used for the flux calculation (see point 6 below).

5). Perform the transient flow simulation for one second:

PMWIN calculates and saves the subsurface fluxes between each finite-difference block.

6). Calculate the flux interaction between groundwater and surface water.

The groundwater in- and outflows from or to surface water bodies are calculated by using the water budget calculator of PMWIN. This calculator requires that different subregions be assigned to the surface water body and the rest of the groundwater model domain.

Strictly speaking, this approach is unusual in building and running a groundwater flow model. Here, the computer program is used as a tool to calculate groundwater flow for each block under the given transmissivity and groundwater level values. The governing equation behind this approach is Darcy's law. The short 'simulation' duration of one second, and a high storage value is used so that the given groundwater level remains practically unchanged when the groundwater flow is calculated.

5.3.2.3 Estimation of the Leakage Rate from / to Vertically Adjacent Aquifers

If an aquifer system includes several aquifers in the vertical direction, the water level difference between neighbouring aquifers will force the exchange of water, which can be estimated by:

$$q_L = C(h_1 - h_2) \qquad (3.4)$$

where

q_L [L/T] = leakage flux between two aquifers per unit square metre

h_1 [L] = head in aquifer 1

h_2 [L] = head in aquifer 2

C [T^{-1}] = resistance factor between aquifer 1 and aquifer 2

The resistance factor C between two aquifers is normally calculated by:

$$C = \frac{2K_1 \cdot K_2}{H_1 \cdot K_2 + H_2 \cdot K_1} \qquad (3.5)$$

where

K_1 [L/T] = VERTICAL HYDRAULIC CONDUCTIVITY OF AQUIFER 1

K_2 [L/T] = VERTICAL HYDRAULIC CONDUCTIVITY OF AQUIFER 2

H_1 [L] = THICKNESS OF AQUIFER 1

H_2 [L] = THICKNESS OF AQUIFER 2

Similar to section 5.3.2.2, the computer program PMWIN5 can be used to calculate the leakage rate between two aquifers:

- Discretize the study area
- Assign top and bottom elevations of aquifers to each block
- Assign the measured groundwater level to each block
- Assign transmissivity or horizontal hydraulic conductivity values to each block
- Assign vertical hydraulic conductivity values to each block
- Assign a high storage value to each block
- Perform a transient flow simulation for one second
- Calculate the flux between the two aquifers

5.3.2.4 Estimation of the Leakage Rate from/to Horizontally Adjacent Aquifers

The calculation of over-boundary flow rates can be omitted if natural no-flow boundaries are used as the boundaries of the study area (e.g. groundwater divides, impermeable fault or rock). If it is not possible, the over-boundary flow can be estimated by using the computer program PMWIN 5. The steps 1) to 5) are same as those of section 5.3.2.2. The last step is:

6). Calculation of over-boundaries flow:

A strip along the boundary of the study area is assigned to a subregion, and the water budget calculator is used to compute the in- and outflows to the subregion. The value of the inflow is equivalent to the groundwater outflow over the boundary (water leaving the system). The value of outflow is equivalent to the groundwater inflow over the boundary (water entering the system).

In addition, chemical and isotopic analyses of groundwater can also be used to evaluate the inflow rate (Desaullniers *et al.* 1981), and the water balance calculation of neighbouring areas can also provide useful information.

5.3.2.5 Estimation of the Existing Groundwater Abstraction

Existing groundwater abstractions can only be obtained through investigation of the abstraction boreholes within the study area. Existing databases, e.g. the National Groundwater Data Base (NGDB), should be used. It should be noted that not all of the boreholes are registered in the database. If a useful database does not exist, information such as land-use maps (for estimating irrigation) and population water usage (for estimating drinking and industrial uses) can be used to estimate the existing abstraction rate. At a comprehensive level, a hydrocensus should be carried out.

5.3.2.6 The Basic Human Needs Reserve and the Ecological Reserve

The basic human needs Reserve is obtained by the product of the groundwater-dependent population and 25 l/day per person (Water Service Act: Act No. 108 of 1997). A change in the groundwater-dependent population in future must be considered.

The Ecological Reserve is defined in order to protect aquatic ecosystems. One of the easiest ways (but not always the best) to protect aquatic ecosystems is to prevent these systems from changing unnaturally. This means that the estimated groundwater discharge to aquatic ecosystems or surface water bodies (i.e. rivers, wetland, springs) should not be greatly affected by allocaton for further uses. It is therefore suggested that this groundwater discharge be treated as a required Ecological Reserve. In doing so, we obtain a conservative, but safe, solution.

5.3.3 Numerical (conceptual) model of the groundwater regime

For numerical (conceptual) modelling, the following software is easy-to-use and available either free of charge or at a nominal cost:

1. Aquifer Simulation Model for Windows (W-H Chiang *et al.*, 1998) is a public domain two-dimensional finite-difference groundwater flow and transport model (includes particle tracking, finite-difference transport and the random walk method). This code is used worldwide by thousands of professionals.

2. Processing Modflow for Windows (W.-H. Chiang, W. Kinzelbach, 1998) is an integrated graphical simulation system for the three-dimensional models MODFLOW, MT3D, MT3DMS, MOC3D, PMPATH 99 and inverse models PEST and UCODE. Many universities, research institutions, and government agencies around the world are using the PMWIN software as a standard groundwater modelling tool.

3. AQUAMOD for Windows (Van Tonder and Buys, 1996) is a public domain two-dimensional finite element groundwater model (includes a mesh generator, flow simulation, transport simulation, risk analysis and inverse modelling). The code is a result of a WRC project and has been applied by many professionals in South Africa.

5.3.4 Determine the groundwater component of Reserve and the allocatable groundwater

All the terms used in the water balance model, and the calculation scheme are summarised below:

- Inflow to the aquifer (groundwater):

    Groundwater recharge (Mm^3/a)

    Leakage rate from surface water (Mm^3/a)

    Leakage rate from horizontally adjacent aquifers (Mm^3/a)

    Leakage rate from vertically adjacent aquifers (Mm^3/a)

    Total inflow (Mm^3/a)

- Outflow from the aquifer (groundwater):

    Existing abstraction (Mm^3/a)

- Leakage rate to surface water (Mm^3/a)

    Leakage rate to horizontally adjacent aquifers (Mm^3/a)

- Leakage rate into vertically adjacent aquifers (Mm^3/a)

    Total outflow (Mm^3/a)

- Groundwater component of Reserve:

    Basic human needs in area of use (BHN) (Mm^3/a)

    Ecological Reserve in discharge position (Mm^3/a)

- Allocatable Groundwater (potentially):

    Allocatable groundwater = Total Inflow - Existing Abstraction (excluding BHN) - BHN – Ecological Reserve

Allocatable groundwater should be developed outside buffer zones in order to protecting the Reserve and RQOs.

5.3.5 Reconciling the results with IFRs

The present approach is to assume that the maintenance low flow requirement of the IFR can be met from Groundwater. In comparison to surface run-off, groundwater flow to surface water bodies is relatively invariable. Groundwater discharge time series should be generated based on approaches discussed in previous chapter. It is important to further consider the determination of the groundwater component of the Reserve, and allocation of the groundwater resource in terms of monthly values. This is still an issue that needs to be further investigated in consultation with hydrologists.

5.4 Presentation of Summary Water Balance Information

The above information on water balance may be summarised annually as shown in Figure 5.2. The purpose of this approach is to establish a user-friendly interface so that scientific information can be implemented by water managers at CMAs.

Characteristics of Aquifer Units:		6	
Q-catchment:	< M10d	Total area(Km²):	30
Relevant IFRsite:	6	SiteName:	swartkops estu
EcoReserve(Mm³/a):	13.0114	Baseflow(Mm³/a) within unit:	0.00
Geology:		Quarternary deposit	
RechargeArea(km²):	15	RechargeMethods:	notsure
MAP(mm): 450	Re(%MAP):	14 WT-ET(Mm³/a):	10
Existing BHs:	0	Water type (Durov):	1
Pumpage(m³/d):	0	Springflow(Mm³/a):	0
AquiferHydraulics:	unconf	GW Depths:	50
Interact with other units:		notsure	
Inflow(Mm³/a):	0.00	Outflow(Mm³/a):	0.00
Interact with SW:		notsure	
Inflow(Mm³/a):	0.00	Outflow(Mm³/a):	0.00
Population:		0	
BHNs(Mm³/a):		0	
Allocation(Mm³/a):	9.45E-01	Confidence(%):	62.5

Figure 5.2: Summarised information on the characteristics of aquifer units: example.

Similar to surface water approach, assurance analysis of generated groundwater contribution is required by presenting duration curves at either annual or monthly basis.

5.5 Quality aspect of the Reserve

Limits on abstraction may be placed where negative quality impacts could occur. For instance, coastal saline intrusion or upconing could result in higher salinity baseflow to a river.

One of other issues, which is not addressed in our report, is how to deal with the Reserve in mines. Should a preliminary Reserve for a mine be determined for purpose of an licence application, the quality aspects of Reserve should be very priority (and also quantity if they are still dewatering). For instance, at the coal mines the problem is usually decanting of groundwater to surface (with a very high sulphate load). The quality Reserve is thus very important for mines. Seepage of polluted groundwater to rivers (or springs) must be investigated.

5.6 On-going Model Calibration

The objective of this section is to initiate a follow-up process. The Reserve determined based on the above methods is subject to review from time to time, and is to be adjusted if necessary. Here an emphasis is placed on on-going model calibration, using data from a monitoring programme (see Chapter7).

6. Resource Quality Objectives

6.1 What are Resource Quality Objectives?

The NWA states that Resource Quality Objective (RQOs) may relate to:

1- The Reserve;

2- instream flow;

3- water levels;

4- the presence and concentrations of particular substances in the water;

5- the characteristics and quality of the water resource and the instream habitat and riparian habitat;

6- the characteristics and distribution of aquatic biota;

7- the regulation or prohibition of instream or land-based activities which may affect the quantity of water in or the quality of the resource;

8- any other characteristic of the water resource in question.

RQOs provide goals within the management class. They are set by the Minister during the process of classification of significant water resources. They may be seen as goals to aim for, if the management class represents an improvement on an impacted resource, or thresholds or safety nets which represent the limit of acceptable impact. They may be numeric or descriptive.

In determining RQOs, a balance must be sought between the need to protect and sustain water resources on the one hand, and the need to develop and use them on the other. Once the class of a water resource and the resource quality objectives have been determined they are binding on all authorities and institutions when exercising any power or performing any duty under the NWA.

6.2 RQOs and groundwater

Following on from the generic description of RQOs given above, RQOs for groundwater could include:

1. Water levels, groundwater gradients, storage volumes and quality parameters required to sustain groundwater component of Reserves for basic human needs and baseflow to springs, wetlands, rivers and estuaries.

2. Groundwater gradients and levels required to maintain the integrity of the aquifer and the aquifer's broader functions.

3. The water table or piezometric levels.

4. The presence (or not) of dissolved and suspended substances (naturally occurring hydrogeochemicals and contaminants).

5. Aquifer parameters such as permeability, storativity and recharge; landscape features such as springs, sinkholes and caverns characteristic of the aquifer type; subsurface and surface ecosystems in which groundwater fulfils any vital function.

6. Aquatic biota in features dependent on groundwater baseflow, such as rivers, wetlands, and caves, or biota living in the aquifer itself.

7. Surface land uses which impact recharge quantity or quality and subterranean activities, such as mining or waste disposal, which impact the aquifer directly. [This would exclude activities which impact or occur solely in aquitards.] The control of land-based activities would lead to protection zoning of land-use.

8. Take your pick!

It is clear from the description above that RQOs can include any requirements or conditions that may need to be met to ensure that that the water resource is maintained in a desired and sustainable state or condition (MacKay 1998a). RQOs are seen to be particularly important for groundwater resources as there is no restriction to aquatic systems, therefore the full ecosystem functioning of groundwater may be recognised and protected where necessary.

6.3 Towards Setting Comprehensive RQOs

Guidelines for setting comprehensive groundwater RQOs will be needed to ensure continuity in establishing legally and scientifically defensible objectives. A WRC project to establish these guidelines is underway and the outputs from that project will be used to complete the guidelines fro the overall RDM.

It is envisaged that the comprehensive RQO procedure should be developed in consultation with a significant cross section of hydrogeologists, water resource managers, other teams within the RDM programme and the teams establishing the National Groundwater Information System and the Water Resources Management Assessment and Information System. RQOs are an integral part of classification and should be developed closely with the classification system.

The Act makes it quite plain that the relevant management authority (e.g. a Catchment Management Authority (CMA)) is responsible, together with the group preparing the Comprehensive Reserve Assessment and DWAF for establishing these objectives. These objectives must then be published for public comment and review. It does not explicitly state so, but it is clear from the compostion of, for example, a CMA, that user groups will also participate in the formulation of these objectives.

The accompanying volume on 'Assessing Vegetation Ecosystem Dependence on Groundwater' gives a procedural outline of who, how and what should be considered in formulating RQOs to protect these ecosystems.

Building on the experience gained during this project, it is proposed that a functional approach should be adopted to formulate RQOs. This functional approach should consider all direct and indirect uses of groundwater by humans and the environment. It should include the ecological role of groundwater and therefore give consideration to ecosystem boundaries, functions, objectives and cummulative effects (Neufeld, 2000). An ecosystem approach is governed by a shared vision of the ecosystem that includes specific goals and measurable ecosystem objectives (Neufeld, 2000). The role of aquifers in the broader environment typically includes providing drinking water for humans, baseflow to rivers, water to plant communities, contributing nutrients to coastal environments, etc.

The potential functions of aquifers in the environment could be summarised as providing:

- Sources or sinks for water
- Sources or sinks for nutrients
- Habitat

Once the various functions have been identified, objectives should be formulated to safeguard those functions. The objectives should be practically measurable and preferably summarised as key indicators. For example, a groundwater dependent plant community would be impacted by a change in the quality and availability of groundwater. The RQOs for this function could be expressed in terms of a maximum water table (spatially and temporally referenced) and a TDS limit. These indicators require the maintenance of a host of other hydrogeological parameters such as groundwater gradients, macrohydrochemistry, etc.

6.4 Levels of Determination

Hydrogeologists and ecologists should provide a comprehensive assessment of the role of aquifers in the catchment and the objectives which would measurably safeguard those functions. A heirarchical approach is probably appropriate for comprehensive level determination. This may be down-scaled to a simpler checklist for the rapid and intermediate levels.

The level at which the RQOs are set should be decided by the CMA (including stakeholders) once they are informed about the relative risks, costs and benefits. At a comprehensive level these will be best communicated by the specialists in terms of future scenarios and a broad group of stakeholders should be involved in the decision process. At an intermediate and rapid level of RDM, where resources are not under stress, the CMA will take the decision on the level of RQOs. An RQO which safeguards a vital function, such as the provision of drinking water from a sole source aquifer, would be set conservatively with a low risk of affecting this function of the resource. Once the RQOs have been set, it is envisaged that the onus will be on licence applicants to demonstrate that their use of water cannot be reasonably foreseen to impact the RQO.

It should be remembered that the effects of changes in groundwater ecosystem functions are in many cases, unknown. They may be directly proportional (whether linear or non-linear) or they may take the form of abrupt changes as critical thresholds are exceeded. The expected nature of the change (gradual or abrupt) should also influence the risk level which is accepted and the type of monitoring programme undertaken.

In summary, a range of hydraulic, hydrochemical and biotic indicators could be selected to indicate that aquifers are effectively fulfilling their important functions in the environment.

RQOs and the RDM Process

Figure 6.1 provides and overview of the RQO process and indicates wher is is part of, or influenced by outputs from, the overall RDM process. Most RQOs will be set in relation to the reference conditions. Exceptions will include controlled activities which are not part of the reference conditions of the catchment.

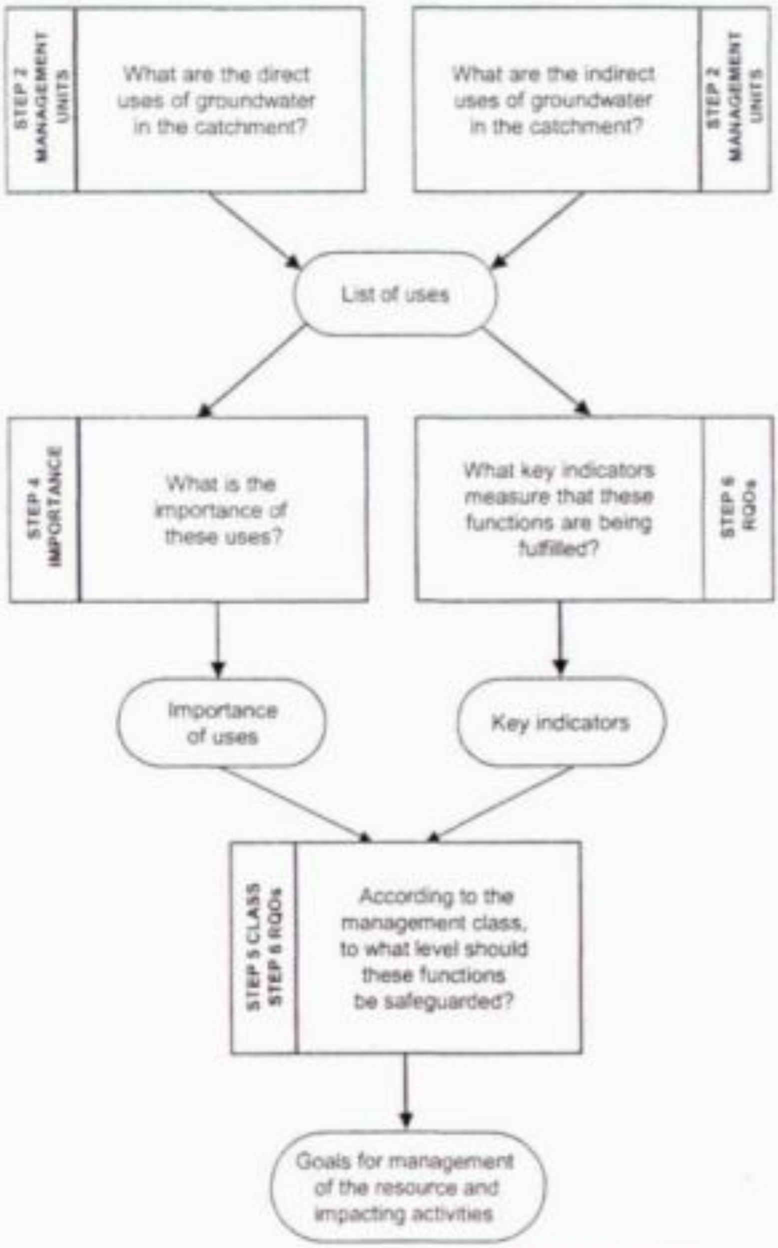

Figure 6.1: Process of determining Resource Quality Objectives for Groundwater.

6.5 Legal mechanism to protect groundwater in other countries

This section gives a summary of legal mechanisms to protect groundwater resources in other selected countries. This shows the legally defensible methods employed elsewhere and underlines the importance of land-use planning controls on in protecting groundwater recharge areas and abstraction zones.

6.5.1 *United States*

The philosophy of groundwater resources protection in the US is underpinned by the following principles:

- Differentiated approach: risk based;
- Precautionary approach: prevention is better than cure;
- Threshold method to limited impacts

The activities of groundwater protection involve a large group of participating entities. They include the all levels of government, Watershed management and interest groups.

Clean Water Act	Many water Programs have been set up by the federal government and adopted by state governments. The Clean Water Act was firstly released in 1972, and its release effectively controlled and improved the point-source pollutions from industries and municipalities. In 1987, the Clean Water Act was amended, and non-point source pollution controls were added. The USEPA is authorized to carry out the non-point source management program. State governments must make their own plans, and seek financial support from the federal government. A huge amount of money has been injected into this program to support legislation, technical research, education, and monitoring.
National Water Quality Program	In 1991, the USEPA set up a new sub-Program: the National Water Quality Program. Its aims are to assess the efficacy of non-point source pollution control in Watersheds, and to further understand the non-point source pollution. Selected watersheds, or catchments, have been chosen to conduct the 6 - 10 years monitoring program on non-point source pollution and to assess efficacy of improving land use.
Sole Source Aquifer Program	In 1987 the USEPA initiated the Sole Source Aquifer Program, its aims are to assess the impacts on sole source aquifer of building new highways, to protect the public water supply boreholes and pipelines, and to manage the disposal of waste water. However, the Sole Source Aquifer Program has not been successful, because some important and sensitive aquifers were not included and no participating and financial support from federal government, state government and local government has been given.
Comprehensive State Groundwater Protection Program	In 1996, the Comprehensive State Groundwater Protection Program was started. It is based on the Safe Drinking Water Act Amendments. This Program emphasizes the integrated management of groundwater and surface water. Its aim is to protect groundwater from pollution, and consider vulnerability and sensitivity of
National Water Source Water Assessment and Protection Program	

	groundwater when defining protection and remediation options. This Program considers groundwater resources, surface water resources and related ecosystems. The Sources Water Assessment and Protection Program was initiated by USEPA in 1996. It emphasises the water resources protection, pollution prevention of water resources, and guarantee of water supply. It includes delineation of water resource protection zones, inventory of contaminants, etc. The goal of this Program is that the water supply for 60% of Americans will come from source water protection systems in 2005. Water quality - the concentrations of key water quality constituents, including their seasonal and inter-annual variability, and going as far as diurnal patterns of variability for constituents such as temperature, dissolved oxygen and pH where relevant;
Wellhead Protection Program (WHPP)	The Wellhead Protection Program (WHPP) is a community–based approach to protect groundwater that supplies public water wells and wellfields. Section 1428 of the Safe Drinking Water Act Amendments of 1986 requires each state to develop and implement a Wellhead Protection Program that sets programmatic guidelines and regulations. This program includes: the roles and duties of the participating entities at all levels of government; how to delineate the wellhead protection area; how to identify and inventory all potential sources of contamination; how to manage potential sources of contamination; contingency plans to protect local water supplies in the event of an emergency; how new wells will be brought into the program, and how the public will participate in program development. This WHPP recognizes that residents of the community are best equipped to address local groundwater protection, thus the WHPPs developed at the local level are the key to the success of the overall program. This program has not finished yet, and the states are considering joining the WHPP with other programs, e.g. Sources Water Assessment and Protection Program, Comprehensive State Groundwater Protection Program.

There are many references related to these programs, which includes how these program were carried out, case studies, etc.

The USEPA's website is the best: www.epa.gov as well as USGS website: www.usgs.gov. In addition to the relevant documents, many software or tools used to assess groundwater resource also are accessible to the public here.

6.5.2 China

In China, about 16% water supply is from groundwater. In some areas, especially in northern China, groundwater exploitation accounts for over half of water supplied. Excess abstraction in some areas has already caused degradation of groundwater resources and deterioration of the ecological environment. To protect important resources, the Chinese government has constituted many related regulations and acts to protect and optimally use the groundwater resources.

6.5.2.1 Pollution Prevention zone for Drinking Water Sources

The Regulation of Managing the Pollution Prevention zone for Drinking Water Sources was constituted in 1989, its purposes is to prevent drinking water source from pollution by delineating protection zones. The protection zone is grouped into three levels according to the threat.

Pollution Prevention zone for Drinking Water Sources	The Regulation of Managing the Pollution Prevention zone for Drinking Water Sources was constituted in 1989, its purposes is to prevent drinking water source from pollution by delineating protection zones. The protection zone is grouped into three levels according to the threat.
Level 1	The first level protection zone is in the vicinity of the abstraction boreholes. Its aim is to guarantee sufficient travel time of water to the borehole to allow for degradation of bacterial pathogens. If necessary, the recharge areas that directly affect the water quality of abstraction also should be included. There are very strict limitations of land use for this zone. No building is allowed for purposes other than water abstraction; no waste disposal is allowed in this zone; no pipes or canals transferring potential pollutants, such as waste water or oil, pass this zone; no oil storage and graveyards are allowed in this zone, etc.
Level 2	The second level protection zone is located outside of the first level zone, it aims to guarantee enough delay time of water accumulation to borehole for preventing other pollutions except the general pathogen pollution. In this zone, no industrial factory or company, which produce or use any potential pollution substances such as for chemistry, oil, radioactive substance, etc, can be built in this zone, if already there are any of these, must be moved out or must ensure that no pollution will be released; no landfill or dump-site are allowed in this zone. If there are, they must be moved out. No polluted water can be used for irrigation.
Level 3	Quasi-protection zone is located outside of the second level protection zone, and include the recharge area that is not included in the other zones. This protection zone is aimed at protection of water quantity and quality in recharge zones. No dumpsite, waste

	disposal site are allowed in this zone, if it is really necessary to have this site in the zone, the permission must be obtained from the relevant environmental department, and special measures must be used to prevent the infiltration of pollution to groundwater.

Different limitations of land use have been set for different protection zones. For instance, in the first level protection zone, no waste disposal. These protection zones will be located in the map for easy management. Local environmental agencies are responsible for the management of protection zone.

In addition, some regulations also are constituted to regulate the groundwater assessment, which includes how to evaluate the quantity and quality of groundwater resources, what precision the evaluation should be according to the different survey stage. It requires the assessment must inventory the possible pollution sources for the groundwater, and assess the risk of pollution. The monitor network must be design for monitoring the groundwater level and quality, and the result can be used for further groundwater study and management.

Although these regulations are successful in protecting groundwater from pollution, but because of the economical reason, not all the people and industrial company realize the importance of groundwater protection. Excessive extraction of groundwater and random disposal of waste already cause the degradation of aquifer. For instance, in northern China plain, a regional groundwater depression has been formed due to the excessive groundwater abstraction. In addition, the groundwater management also need be improved. Groundwater data are hold in different sectors and in different forma. It is necessary to build up a data shared system to reduce duplicate work. The new legislation also is constituted for building a better management system of groundwater exploitation. Public education is necessary to make the people to realize the importance of the environment and groundwater, and start to act for saving water and against any potential threat to groundwater system.

6.5.3 Australia

In Western Australia, the Water and Rivers Commission is responsible for the protection of water sources used for public drinking supply. The Public Drinking Water Source Areas (PDWSAs) are defined as lands proclaimed under the Metropolitan Water Supply Sewerage and Drainage (MWSSD) Act, 1909 and the Country Areas Water Supply (CAWS) Act, 1947 to allow the protection of water sources for public drinking purposes. This includes Underground Water Pollution Control Areas (UWPCAs), Catchments Areas (CAs) and Water Reserves (WRs). The Water and Rivers Commission defines three levels of priority classification for protection of water resources in PDWSAs.

Priority 1	Priority 1 (P1) source protection areas are defined to ensure that there is no degradation of the water source. P1 areas are declared over land where the provision of the highest quality public drinking water is the prime beneficial land use.
Priority 2	Priority 2 (P2) source protection areas are defined to ensure that there is no increased risk of pollution to the water source. P2 areas are declared over land where low intensity development (such as rural) already exists. Provision of public drinking water supply is a high priority in these areas.
Priority 3	Priority 3 (P3) source protection areas are defined to minimise the risk of pollution to the water source. P3 areas are declared over land where drinking water supply needs co-exist with other land uses such as residential, commercial and light industrial developments. Protection of P3 areas is achieved through management guidelines rather than conditions on land use. Many policies have been set up to protect the water resources and its related environmental values (http://www.wrc.wa.gov.au/protect/index.html).
Construction and Silica Sand Mining in Public Drinking Water Source Area (1999)	The objective of this policy is to protect water quality and quantity within Public Drinking Water Source Areas from the adverse impacts of sand mining operations, and ensure that all sites are rehabilitated to an acceptable standard. The guidelines provide a range of standards and criteria for the management of potentially polluting components of sand mining operations. These standards will constitute the following conditions for approval: minimum final clearance to the groundwater table; control of methods of fuel storage, and management of fuel; management of plant and equipment servicing; management of waste disposal; the specification of intended end land use activities the implementation of guidelines for end land use activities and rehabilitation programs that have been approved by the Commission.
State Water Quality Management Strategy (2000)	The policy and guidelines also provide information on water resources management by agencies regulating sand mining. This policy will be implemented through the Department of Minerals and Energy's and local government agencies' approval procedures, and through Acts and by-laws administered by the Commission. The Commission has the statutory responsibility to license water
Pesticide use in Public Drinking Water	

Source area (2000)	abstraction and to apply by-laws to control activities that have the potential to pollute, through permits. This policy is based on the National Water Quality Management Strategy (NWQMS), which has been jointly developed by the Agriculture and Resource Management Council of Australia and New Zealand and the Australian and New Zealand Environment and Conservation Council with input from the National Health and Medical Research Council. Western Australia has been an active participant in NWQMS. The State Water Quality Management Strategy (SWQMS) has been developed to implement the NWQMS in Western Australia. It provides policies, a process and a series of guidelines for water quality management. It balances the social and economic factors and conservation of the national environment.
Draft Policy for Access to Land within Public Drinking Water Source Area (2001)	The objective of this policy is to protect drinking water from contamination by the use of pesticides in the interest of public health. Pesticide, as defined under this policy, refers to a substance or compound used or intended for use for agricultural, pastoral, horticultural, domestic, or industrial purposes for controlling, destroying or preventing the growth and development of, any fungus, virus, insect, mite, mollusc, nematode, plant or animal and includes all preparations and admixtures containing any proportion of any one or more of them. This policy gives the detail regulations in respect of Pesticide use in Public Drinking Water Source Areas, Transportation of pesticides, Disposal of pesticides, equipment and containers, Maintenance and cleaning of pesticide equipment, Mixing and storage of pesticides, Monitoring and auditing, Clean up of contamination, etc.
Ribbons of Blue	The Draft Policy for Access to Land within Public Drinking Water Source Areas (2001) is to protect: Drinking water sources from contamination by inappropriate recreational activities in the interest of public health, and The environmental and ecological values of water supply sources used for purposes other than drinking supply. These environmental and ecological values may include: Protection of aquatic system, recreational water quality and aesthetics, agricultural water use, and industrial water quality. This policy is consistent with the principles of water source protection: differential protection of public drinking water sources areas, protection of vulnerable areas, justification for policy, catchment management. This policy also gives the guidelines for recreation, such as land-based recreation, water-based recreation, catchments of future water sources, catchment management within PDWSAs, future investigation, etc.

	Ribbons of Blue (http://www.wrc.wa.gov.au/ribbons/index.html), an environmental education network, has been set up, which is aimed at increasing community awareness and understanding about local water quality, and taking action for a better environment. It involves school students and community groups in monitoring water quality. Data collected from the sampling provides valuable information for identifying environmental problems and preparing management plans. Based on the outcomes of their monitoring, participating groups may develop action strategies to help manage any problems identified.

Legislation and policy have played important roles in environmental protection, but this approach rarely provides the whole solution in environmental protection. Good land use planning is essential and this can only be achieved if planners, developers and the community are aware of the issues of natural resource management. It is realized that community involvement is very important, therefore partnerships with the community are built on common understanding, trust, mutual respect and an ongoing commitment to achieving results.

7. Conclusion and Recommendation

The following outputs are completed:

- Determination of the Resource Directed Measures: Groundwater Component (version 1.1)
- Terrestrial Groundwater Dependence Ecosystems (version 1.1)
- Reports of four case studies
- Software: Groundwater Reserve Quantification (GWRESERVE_Ver1) and its adaptation
- Software: Updated Recharge Programme (Recharge)
- Hydrograph-separation Programme (Baseflow)

It is clear that the overall objectives, as set in the research projects and amended during integration into the RDM programme, are met.

For purpose of groundwater protection, all three mechanisms of the RDM, namely Classification, Setting of the Reserve and Resource Quality Objectives, should be used. It is recommended that the proposed methodology for determination of groundwater component of RDM be applied and verified so that it can be further improved through application.

As pointed out previously, the RDM determination may be called a rapid, intermediate or comprehensive evaluation. The latter may be achieved through improvement and upgrading of the former into a more comprehensive and accurate Reserve assessment as more information becomes available. However we have been convinced through case studies that a single approach should be used for the determination of the groundwater component of the RDM with confidence levels ranging from rapid to comprehensive. A follow-up monitoring programme must be initiated in order to assist with review process from time to time (every 5 years).

Areas identified for further attention include:

Classification –

- It is suggested that the Department of Water Affairs play a key role in negotiating access with the custodians of key datasets and invest in defining relevant attributes from existing datasets, such as Land Type, for use in the Classification. A standardisation of principal datasets for RDM would enable greater defensibility and comparison of outputs at a rapid and intermediate level. The Department also needs to examine how groundwater data from the NGDB and hydrogeological map series can be made more readily available for use in Classification.

- A greater understanding of the in-situ environmental use of groundwater in South Africa is needed in order to effectively set RQOs. It is hoped that this will be addressed through a WRC project on Groundwater Dependent Ecosystems in South Africa.
- Vulnerability assessments are one of the most important contributions from groundwater specialists to the Classification process. We need to examine in more detail to determine with reasonable confidence the vulnerability of secondary aquifers at a catchment scale. It is recommended that the WRC should consider further investment in refining this component of the methodology.

Reserve Quantification –

- It is problematic, if not impossible, to regulate groundwater contributions to meet IRFs on a monthly basis.
- Chemical reactions associated with interaction between groundwater and surface water.
- Cost implications of Reserve determination at different levels.

Resource Quality Objectives –

- Little work is available in South Africa regarding biotic indicators (e.g. hypogean life or groundwater ecosystem). More research in this area should be undertaken to shed light on state of aquifers that may interact with surface water bodies.

Crisis management –

- Although one of the primary purposes of doing monitoring is to provide information for better understanding of groundwater flow systems (hence leading to improvement of the Reserve setting) a crisis could arise should borehole yields drop considerably or water quality deteriorate. Swift management responses are required to avert serious problems.

- For management of borehole abstraction, a tolerable drawdown should be set for each borehole, depending on the hydrogeological circumstances. Monitoring will provide early warning of possible exceedence of tolerable limits and the initial management response can be assessed by means of a single decision tool adopted by the catchment authority.

- For management of water supply quality, a tolerable limit should be set for various problem constituents based on the water quality guidelines adopted by DWAF. Quality monitoring will provide early warning of possible exceedence of tolerable limits.

If a water source is believed to be contaminated, it should be reported to the catchment authority, who upon receiving such an inquiry will arrange for a hydrogeologst or technician to study the available information on the source, visit the site, and sample the source if necessary. If the nature and extent of pollution can be established or confirmed, it must be brought to the attention of the relevant management for a decision regarding provisional arrangement for community water supply.

8. Glossary

Actual evaporation - the amount of water evaporated under a given set of circumstances where water supply limits evaporation (as opposed to potential evaporation, which is evaporation under unlimited circumstances, as from an evaporation pan. Symbol AET or Aet or E_a.

Alluvial aquifer - an aquifer formed of unconsolidated sediments deposited by a river or stream; typically occurring beneath or alongside a current channel, or in an buried old or paleo-channel of the river.

Aquatic ecosystem - Not defined in the Water Act. They are defined in the water quality guidelines (DWAF 1996) as: the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs lakes and wetlands and their fringing vegetation. Terrestrial biota, other than humans dependent on aquatic systems for their survival are included in this definition.

Aquifer (Driscoll, 1986): A formation, group of formations, or part of a formation that contains sufficient saturated permeable material to yield economical quantities of water to wells/boreholes and springs; (Water Act, 1998) A geological formation which has structures or textures that hold water or permit appreciable water movement through them

Aquifer test (Driscoll, 1986): A test involving the withdrawal of measured quantities of water from or addition of water to a well and the measurement of resulting changes in head in the aquifer during and after the period of discharge or addition.

Baseflow (Base flow): is referred to as delayed flow components with groundwater as dominant component (Singh, 1988).

Biome: A broad ecological unit representing major life zones of large areas. In South Africa these are defined mainly by vegetation structure and climate (Low and Rebelo, 1996).

Borehole: Includes a well, excavation or any artificially constructed or improved underground cavity which can be used for the purpose of *(a)* intercepting, collecting or storing water in or removing water from an aquifer; *(b)* observing and collecting data and information on water in an aquifer; or *(c)* recharging an aquifer;

Capillary fringe: The lower division of the zone of aeration (vadose zone) that overlies the zone of saturation and in which the pressure of water in the interstices is less than atmospheric (McGraw-Hill, 1978).

Catchment: In relation to a watercourse or watercourses or part of a watercourse, means the area from which any rainfall will drain into the watercourse or watercourses or part of a watercourse, through surface flow to a common point or common points;

Confined Aquifer: An aquifer that is confined between two less-permeable confining beds. The confining bed has a significantly lower hydraulic conductivity than the aquifer.

Discharge (Water words dictionary, 1999): In its simplest concept, discharge means outflow and is used as a measure of the rate at which a volume of water passes a given point. Therefore, the use of this term is not restricted as to course or location, and it can be used to describe the flow of water from a pipe or a drainage basin. With reference to groundwater, the process by which groundwater leaves the Zone of Saturation via Evaporation, Evapotranspiration, or by flow to the surface through springs and seeps.

Dykes: A tabular body of intrusive igneous rock that cuts across the layering or structural fabric of the host rock. It may be a composite or multiple intrusion. Dykes may be fine, medium or coarse grained, depending on their composition and the combination of their size and length of their cooling period. They vary in width from a few centimetres to many metres, but they may be traced for several kilometres. A group of dykes is called a dyke swarm.

Ecoregion (DWAF, 1998): The breakdown of a catchment into water resource units for the purpose of determining the Reserve for rivers. It is done primarily on a biophysical basis, according to the occurrence of different ecological regions within the catchment.

Ecosystem: An interconnected and interacting system comprising living organisms - including animals, plants, fungi, and microorganisms - and their non-living environment.

Ephemeral - rivers, streams or pans which are ephemeral are fed by inflows of surface water after rains and are seasonal. There is no groundwater contribution (baseflow) therefore these are influent features which, in permeable areas, recharge groundwater.

Estuary: A partially or fully enclosed body of water which is open to the sea permanently or periodically; and within which the sea water can be diluted, to an extent that is measurable, with fresh water drained from land.

Evaporation: The total loss of water in vapour form from all sources - open water, from the plant surface (interception), through plants (transpiration) and from the soil surface: it involves the transition of water from the liquid phase to the vapour phase, and during this process energy (termed latent heat) is absorbed.

Evapotranspiration: The refers to that component of the evaporated water that comes from transpiration by, or interception losses, from plants. In modern usage it is often replaced by the term evaporation, as defined above.

Fault (Driscoll, 1986): A fracture or zone of fractures along which there has been displacement of the sides relative to one another, parallel to the fracture.

Finite-difference model: A particular kind of digital computer model based upon a rectangular grid that sets the boundaries of the model and nodes, where the model will be solved.

Finite-element model: A digital groundwater flow computer in which the aquifer is divided into a mesh formed of a number of polygonal cells.

Geohydrology (Vegter, 1995): The branch of hydrology dealing with subsurface water ie water in both the saturated and unsaturated zones. Also used interchangeably with hydrogeology.

Geological formation: - the fundamental lithostratigraphic unit and may consist of consolidated or unconsolidated material (Bates and Jackson 1980). This definition could arguably include formations such as the Kalahari sands and the Quaternary sands of the dune fields in the Western Cape.

Geological formation: The fundamental lithostratigraphic unit and may consist of consolidated or unconsolidated material (Bates and Jackson, 1980). This definition could arguably include formations such as the Kalahari sands and the Quaternary sands of the dune fields in the Western Cape.

Geology (Water words dictionary, 1999): The science that studies the physical nature and history of the earth.

Geomorphology - The study of the configuration of the earth's surface, including classification, description, nature, origin and development and their relationships to the underlying geological structures and the history of geological changes seen in these structures. Includes and has largely replaced the concept and study of physiography (Bates and Jackson 1980).

Groundwater body - in this document the term is used to include both the aquifer in its conventional sense (see definition) and significant volumes of water stored in (deep) colluvial or alluvial deposits or deeply weathered rock (regolith).

Groundwater level (Vegter, 1995): The water level in a borehole/well penetrating the zone of saturation and from which no water is being withdrawn.

Groundwater management unit: An area of the catchment which requires consistent management actions to maintain the desired level of use and protection of groundwater.

Groundwater Modeller: The person to carry out the simulation of groundwater flow and transport, with numerical methods.

Groundwater region : A broad geohydrological grouping based on dominant aquifer type (secondary/ primary), lithostratigraphy, physiography and climate. 64 have been delineated for South Africa (Vegter 2001)

Groundwater response unit:: An aquifer unit or multiple aquifer units with relatively similar hydrogeological characteristics, including permeability, thickness, storage, attenuation potential and hydrochemistry.

Groundwater quality (Water words dictionary, 1999): A term used to describe the chemical, physical, and biological characteristics of groundwater, usually in respect to its suitability for a particular purpose.

Hydraulic conductivity: A coefficient of proportionality describing the rate at which water can move through a permeable medium. The density and kinematic viscosity of the water must be considered in determining hydraulic conductivity.

Hydrology (Vegter, 1995): The science that deals with continental water on and under the Earth's surface.

Hypogean life – life occurring or originating beneath the surface of the earth.

Hyporhoeic zone - the saturated and biologically active zone in and alongside an alluvial river bed. The hyporhoeic zone is important in river system nutrient budgets as it acts as a nutrient storage system (Valett *et al.* 1994). It also provides a habitat and refuge for aquatic organisms, thus also serving a buffering function which promotes rapid recovery of aquatic ecosystems after floods or droughts.

Instream habitat: Includes the physical structure of a watercourse and the associated vegetation in relation to the bed of the watercourse;

Inverse modelling: A modelling technique, which uses measurement data as input, for estimating unknown aquifer parameter values within a modelling area..

Landform: Any physical, recognisable form or feature of the earth's surface having a characteristic shape and produced by natural causes (Bates and Jackson, 1980).

Landscape: An area of the earth's surface including its three-dimensional form as well as the underlying geology that determines the patterns of recharge, storage and discharge of groundwater. In its conventional sense a landscape is an area that be viewed from a single point but as used here it could be larger where this is necessary to include the boundaries and dynamics of particular groundwater bodies.

Landuse (Water words dictionary, 1999): The primary or primary and secondary uses of land, such as cropland, woodland, pastureland, etc. The description of a particular land use should convey the dominant character of a geographic area, and thereby establish the types of activities which are most appropriate and compatible with primary uses.

Lithostratigraphy - the science of classifying or organising rock strata according to the properties of the constituent material (Bates and Jackson 1980).

Management class: The present and historical condition of a water resource, its sensitivity and importance, risk of degradation and its potential for restoration are all factors which determine the management class and the RQOs.

Management unit (DWAF, 1998): A management unit is the breakdown of ecoregions or hydrological regions according to management requirements for surface water resources.

MOC3D: A three-dimensional, finite difference transport model for use with MODFLOW, developed by U.S. Geological Survey.

MODFLOW: A modular, three-dimensional, finite difference groundwater flow model, developed by U.S. Geological Survey.

MT3D: A three-dimensional, finite difference transport model, (usually used with MODFLOW), developed by the hydrological group at the University of Alabama.

MT3DMS: A modular three-dimensional multispecies transport model (mainly for use with MODFLOW), developed by the hydrological group at the University of Alabama.

Numerical model: A model of groundwater flow and/or solute transport in which the aquifer is described by numerical equations, with specified values for boundary conditions, that are solved on a digital computer.

Palustrine wetlands: These are typical wetlands with emergent vegetation which can range from grasses to forest. Lacustrine wetlands are the natural, permanent or seasonal, freshwater lakes. Riverine floodplain wetlands occur on the floodplains of rivers but do not include the riparian systems along the flowing water channels. Endorheic wetlands form in closed drainage areas and include brackish, saline or alkaline lakes, flats, pans and marshes; they can be seasonal or perennial (Cowan & Van Riet, 1998).

PEST: A model-independent parameter estimation program, developed by Watermark Computing. It serves the same purpose as UCODE does

Phreatic surface - the upper limit of the saturated zone i.e. the water table.

PMPATH 99: A interactive particle tracking model for calculating groundwater flow lines, developed by W.H.Chiang (IGS, Bloemfontein) and W. KinzelBach (IHW, Zurich).

PMWIN: Processing Modflow for Windows, a integrated graphical simulation system for the three-dimensional models MODFLOW, MT3D, MT3DMS, MOC3D, PMPATH 99 and inverse models PEST and **UCODE**, developed by W.H. Chiang (IGS, Bloemfontein) and W. Kinzelbach (IHW, Zurich)

Pollution: Direct or indirect alteration of the physical, chemical or biological properties of a water resource so as to make it less fit for any beneficial purpose for which it may reasonably be expected to be used; or harmful or potentially harmful to the welfare, health or safety of human beings; any aquatic or non-aquatic organisms; the resource quality; or property.

Protection: in relation to a water resource, means maintenance of the quality of the water resource to the extent that the water resource may be used in an ecologically sustainable way; prevention of the degradation of the water resource; and the rehabilitation of the water resource;

Rainfall (Water words dictionary, 1999): (1) A shower or fall of rain. (2) The quantity of water that falls as rain in a specified area and time interval. Not strictly synonymous with Precipitation.

Recharge (Vegter, 1995): The processes involved in the absorption and addition of water to the zone of saturation. Synonym: Replenishment.

Reference conditions: Describe the natural un-impacted characteristics of a water resource. Reference conditions include: Water levels, the seasonal and annual variations thereof. Drought scenarios are also included: Water quality - the concentration of the key water quality constituents, including their seasonal and inter-annual variability; Groundwater/surface water interaction (including recharge/discharge); Rainfall; Aquifer structure and integrity.

Regolith - technically a layer of fragmented or unconsolidated rock material, whether residual or transported, of variable character and overlying bedrock (Bates and Jackson 1980). In this document we use regolith in the sense of non-transported material i.e. from in situ weathering.

Remote sensing (Water words dictionary, 1999): The measurement or acquisition of information of some property of an object or phenomenon by a recording device that is not in physical or intimate contact with the object or phenomenon under study. Also, the utilisation at a distance (as from aircraft, spacecraft, satellites, or ships) of any device and its attendant display for gathering information pertinent to the environment, such as measurements of force fields, electromagnetic radiation, infrared sensing, land use, water bodies, etc. Such systems typically employ devices such as cameras, lasers, radio frequency receivers, radar systems, infrared detectors, sonar seismographs, gravimeters, magnetometers, and scintillation counters.

Reserve (National Water Act, 1998): The quantity and quality of water required: to satisfy basic human needs by securing a basic water supply, as prescribed under the Water Services Act, 1997 (Act no. 108, 1997), for people who are now or who will, in the reasonably near future, be relying on, taking water from, or being supplied from the relevant water resource, and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of the relevant water resource.

Riparian: Growing by rivers or streams. The Water Act contains the following definition: riparian habitat" includes the physical structure and associated vegetation of the areas associated with a watercourse which are commonly characterised by alluvial soils, and which are inundated or flooded to an extent and with a frequency sufficient to support vegetation of species with a composition and physical structure distinct from those of adjacent land areas.

Risk: A combination of the probability, or frequency, of occurrence of a defined hazard and the magnitude of the consequences of the occurrence.

Satellite imagery: A digital image captured by a sensor mounted on an earth orbiting satellite.

Specific storage: The amount of water released from or taken into storage per unit volume of a porous medium, per unit change in hydraulic head.

Specified yield: The ratio of the volume of water a rock or soil will yield by gravity drainage, to the volume of the rock or soil. Gravity drainage may take many months to occur.

Stochastic Modelling: A modelling technique, which addresses the uncertainties in numerical groundwater models by considering the variation of aquifer parameters and other model parameters.

Storage coefficient: The volume of water an aquifer releases from or takes into storage per unit surface area of the aquifer per unit change in hydraulic head. It is equal to the product of specific storage and aquifer thickness. In an unconfined aquifer, the storage coefficient is equivalent to the specific yield.

Topography (Water words dictionary, 1999): The general configuration of the land surface including relief and position of natural and man-made features.

Transmissivity: The rate at which water of a prevailing density and viscosity is transmitted through a unit width of an aquifer or confining bed under a unit hydraulic gradient. It is a function of properties of the liquid, the porous media, and the thickness of the porous media.

Transpiration - the loss of water vapour from the living cells in the plant through pores (stomata) in the leaves in vapour form.

UCODE: A computer code for universal inverse modelling, developed by U.S. Geological Survey. It serves the same purpose as PEST does.

Unconfined aquifer: An aquifer in which there are no less-permeable confining beds between the saturated zone and the groundwater surface.

Water balance (Water words dictionary, 1999): (1) A measure of the amount of water entering and the amount of water leaving a system. Also referred to as Hydrologic Budget; (2) The ratio between the water assimilated into the body and that lost from the body; also, the condition of the body when this ratio approximates unity; (3) An evaluation of all the sources of supply and the corresponding discharges with respect to an aquifer or a drainage basin.

Water management area: An area established as a management unit in the national water resource strategy within which a catchment management agency will conduct the protection, use, development, conservation, management and control of water resources;

Water resource: Includes a watercourse, surface water, estuary, or aquifer;

Wetlands: Land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil.

9. References

Baron, J, Seward, P and Seymour, A. 1998, The groundwater harvest potential map of the Republic of South Africa 1996, Technical Report No. GH 3917, Department of Water Affairs and Forestry.

Bates, RL and Jackson, JA (eds) 1980. Glossary of geology. 2nd edition. American Geological Institute, Virginia.

Birkhead, AL, Olbrich, BW, James, CS and Rogers, KH 1997. Developing an integrated approach to predicting the water use of riparian vegetation. Report No. 474/1/97, Water Research Commission, Pretoria.

Braune, E and Dziembowski, ZM 1997. Towards integrated groundwater and surface water management, The Eighth South Africa National Symposium held at the University of Pretoria on Noc. 17-19, 1997.

Bredenkamp, DB, Botha, LJ, van Tonder, GJ and van Rensburg, HJ, 1995. Manual on quantitative estimation of groundwater recharge and aquifer storativity. Water Research Commission Report TT73/95. WRC, Pretoria.

Chiang, W.-H, W. Kinzelbach, 1998, Processing Modflow, A simulation system for modeling groundwater flow and pollution, version 5.0, Institute for Groundwater Studies, University of the Orange Free State, Republic of South Africa.

Chiang, W.-H., W. Kinzelbach and R. Rausch, 1998, Aquifer Simulation Model for Windows - Groundwater flow and transport modeling, an integrated program. Gebrüder Borntraeger Berlin, Stuttgart, ISBN 3-443-01039-3.

Colvin *et al*, 2001. *Assessment of Vegetation Ecosystem Dependence on Groundwater.* Draft report WRC Project 1092.

Department of Water Affairs and Forestry (1998) Part3: Development of the methodology for determination of the ecological Reserve. Pretoria, South Africa.

Department of Water Affairs and Forestry, Department of Health, Water Research Commission, 1998. *Quality of Domestic Water Supplies*, Vols 1 – 5.

Department of Water Affairs 1998, *Minimum Requirements for water monitoring at waste management facilities*, Second Edition.

Department of Water Affairs, 1999. *Water Resources Protection Policy Implementation. Resource Directed Measures for protection of water resources, Integrated Manual*, Report no N/28/99

Department of Water Affairs and Forestry, 2001, *A Guide to Strategic Environmental Assessment for Water Use in Catchments*. Draft Document, September 2001.

Domenico, P.A. and Schwartz, F.W. 1990. Physical and Chemical Hydrogeology. ISBN 0-471-50744-x, John Wiley & Sons, Inc.

Driscoll, F.G. 1986. Groundwater and Wells. Second Edition. Johnson Filtration Systems Inc., St. Paul, Minnesota.

DWAF 1996. South African water quality guidelines. Volume 7: Aquatic ecosystems. Department of Water Affairs and Forestry, Pretoria.

DWAF 1999. Resource Directed Measures for Protection of Water Resources, Volume 2: Integrated Manual Version 1.0, Pretoria.

DWAF 1999. Resource Directed Measures for Protection of Water Resources, Volume 3: River Component Version 1.0, Pretoria.

Department of Water Affairs and Forestry. Proposed First Edition National Water Resource Strategy. Version 1.0: September 2001

Department of Water Affairs 2002, Integrated Water Resource Management Series: Guidelines for Groundwater Management in Water Management Areas of South Africa. February 2002, Working Draft.

Department of Water Affairs 2002, Methods for Assessing Water Quality in Ecological Reserve Determinations for Rivers. March 2002, Draft 15.

Fetter, C.W. 1994, Applied Hydrogeology, 3rd edition, Prentice-Hall, Inc., A Semon & Schuster Company, Upper Saddle River, New Jersey 07458, ISBN: 0023364904.

Flügel, W.A. 1995. Hydrological Response Units (HRU's) as modelling entities for hydrological river basin simulation and their methodological potential for modelling complex environmental process systems. Results from the Sieg catchment. Geographisches Institut der Universität Jena, Lehrstuhl Geoinformatik, Geohydrologie und Modellierung, Löbdergraben 32, D-07753 Jena.

Fraser, BG and Williams, DD 1998. Seasonal boundary dynamics of a groundwater/surface-water ecotone. *Ecology* 79: 2019-2031.

Freeze, R.A. and Cherry, J.A. 1979. Groundwater, ISBN 0-13-365312-9, Pretice-Hall, Inc.

Government Gazette 19182. 1998. National Water Act, Act 38, 26 August 1998. Pretoria, South Africa.

Helmschrot, J. 1998. Evaluation of Hydrological Response Units (HRUs) for Regional Catchment Parameterization in the Umzimvubu River Basin, Eastern Cape Province, South Africa. Geographisches Institut der Universität Jena, Lehrstuhl Geoinformatik, Geohydrologie und Modellierung, Löbdergraben 32, D-07753 Jena.

Herold, C.E. (1980). A model to compute on a monthly basis diffuse salt loads associated with runoff. WRC PWVS project, HRU Report No. 1/80.

Hobbs, P.J.(1996). JICA study-stituation report on geology, soils and hydrogeology of the Maglies Water extended supply area; Report prepared for EVN Conculting Engineers by VSA GeoConsultants, Pretoria.

Hughes, D.A. and Münster, F. 1999 A decision support system for an initial 'low-confidence' estimate of the quantity component of the Reserve for rivers. Institute for Water Research, Rhodes University, South Africa.

Jolly, J.L. and Reynders, A.G. 1993. The protection of aquifers - a proposed aquifer classification and protection zoning for South African conditions. Proc. "Africa needs groundwater". An international groundwater convention. South Africa pp. 1 – 11.

Kirchner and Van Tonder 1995. Proposed guidelines for the execution, evaluation and interpretation of pumping tests in fractured rock aquifers. Water SA, (21) no. 3.

Kirchner, J., Van Tonder, G.J. and Lukas, E. 1991. Exploitation potential of Karoo aquifers. WRC Project no. 170/1/91. Water Research Commission, Pretoria.

Kleynhans, CJ, Silberbauer, M and Kemper, N 1998. Preliminary ecoregion level 1 classification for South Africa. Institute for Water Quality Studies, Pretoria. Copy downloaded from the following Internet address: http://iwqs.pwv.gov.za/wg/waterlaw/index.html.

Kok, TS, 1976. Die geohidrologie van die Bloemendalbasboomplaas, distrik Pietermaritzburg, Natal. Internal report GH.2924, of the Geohydrology Directorate of the Department of Water Affairs and Forestry.

Kresic, N. 1997, Quantitative Solution in Hydrogeology and Groundwater Modeling, Lewis Publishers Inc., ISBN: 1566702194.

Kruseman, G.P. and De Ridder, N.A. 1991. Analysis and Evaluation of Pumping Test Data. Second Edition. International Institute for Land Reclamation and Improvement, PO Box 45, 6700 AA Wageningen, The Netherlands.

MacKay, H 1998. Development of the methodology for determination of the ecological Reserve, draft document for discussion at Crocodile River Pilot Study (2-5 November 1998), Printed October 25, 1998.

MacKay, H 1999. Minutes of RDM Project Steering Committee Meeting, DWAF Pretoris, April 14, 1999.

MacKay, HM 1998a. Towards a classification system for water resources in South Africa. Copy downloaded from the following Internet address: http://iwqs.pwv.gov.za/wg/waterlaw/index.html.

MacKay, H.M 1998b. Part 3. Development of a methodology for determination of the ecological Reserve. Draft Document for discussion dated 25 October 1998.

Midgley, D. C., Pitman, W.V. & Middleton, B. J. (1994) Surface Water Resources of South Africa 1990. Water Research Commission, Pretoria.

Midgley, DC, Pitman, WV and Middleton, BJ 1994. The surface water resources of South Africa 1990. Volumes 1 to 6. Report Numbers 298/1.1/94 to 298/6.1/94 (text) and 298/1.2/94 to 298/6.2/94 (maps). Water Research Commission, Pretoria. Also accompanied by a CD-ROM with selected data sets.

Neufeld, D.A. 2000 An ecosystem approach to planning for groundwater: The Case of Waterloo Region, Ontario, Canada. Hydrogeology Journal Vol 8, No.2.

Parson, R. 1995. A South African aquifer system management classification. WRC Report No KV 77/95, Water Research Commission, Pretoria.

Parsons, R. and Conrad, J. 1998. Explanatory notes for the aquifer classification map of South Africa. WRC Report No KV 116/98, Water Research Commission, Pretoria.

Parsons, R.P. 1999. Preliminary ecological Reserve method: A guide for quantifying the groundwater component—methodology manual, Parsons and Association Specialist Groundwater Consultants.

Parsons, R.P. 1999. Intermediate Reserve method pilot test: Pienaard river between Roodeplaat dam and Klipvoor dam. Parsons and Association Specialist Groundwater Consultants.

Partridge, T. 2001 Personal communication, Partridge, Maud and Associates, P.O. Box 1050, Parklands 2121.

Rorabaugh, M.I. 1964 Estimating changes in bank storage and groundwater contribution to streamflow. International Association of Scientific Hydrology. Publication 63, 432-441.

Sandström, K 1995. Modeling the effects of rainfall variability on groundwater recharge in semi-arid Tanzania. *Nordic Hydrology* 26: 313-330.

Sandström, K 1996. Hydrochemical deciphering of streamflow generation in semi-arid East Africa. *Hydrological Processes* 10: 703-720.

Schulze, RE 1995. Hydrology and Agrohydrology. A text to accompany the *ACRU 3.00* agrohydrological modelling system. Report No. TT69/95, Water Research Commission, Pretoria.

Scott, DF and Le Maitre, DC, 1997. The Interaction between vegetation and groundwater: research priorities for South Africa. Water Research Commission, Pretoria. WRC Report No. 730/1/98.

Singh, VP 1988. Hydrologic Systems: Watershed Modeling, Prentice Hall, 1988.

Smakhtin, VY and Watkins, DA 1997. Low flow estimation in South Africa. Report No. 494/1/97, Water Research Commission, Pretoria.

Smakhtin, V.U. 2001 Estimating continuous monthly baseflow time series and their possible applications in the context of the ecological Reserve. Water SA, Vol. 27, No. 2. April 2001.

Spitz, K and Moreno, J. 1996. A Practical Guide to Groundwater and Solute Transport Modeling, ISBN 0-566770-219-4, John Wiley &Sons, INC., New York, NY.

Tredoux, G. 1993. A preliminary investigation of the nitrate content of groundwater and limitation of the nitrate input; WRC Report No. 368/1/93, Water Research Commission, Pretoria.

Van Tonder, G.J., Buys, J., 1996, AQUIMOD for Windows, Institute for Groundwater Studies, University of the Orange Free State, Bloemfontein.

Van Tonder, G.J., Van Sandwky, L., Buys, J., 1996. Program TRIPOL, version 1.0, Institute for Groundwater studies, and Water Research Commision.

Van Tonder, G., and Xu, Y., 2001. A guide to the Estimation of Groundwater Recharge in South Africa – Presented at a Workshop on Recharge held at the University of Pretoria, for DWAF.

Van Wyk, WL, 1963. Ground-water studies in northern Natal, Zululand and surrounding areas. Geological Survey of South Africa Memoir no. 52.

Vegter, J.R. and Pitman, W.V. (1996) Recharge and stream flow, Workshop on groundwater – surface water issues in arid and semi – arid areas. Organised by the Water Research Commission and IAH (South Africa), Pretoria.

Vegter JR 1995. An explanation of a set of national groundwater maps. Report No. TT 74/95, Water Research Commission, Pretoria.

Vegter, JR and Pitman, WV (1997?), Recharge and stream flow, presented at a workshop on groundwater – surface water issues in arid and semi-arid areas, South Africa, 1997.

Vegter, JR, 1993. Effect of clearing arid sweet bushveld vegetation on Groundwater, Northwestern and Northern Transvaal. Unpublished consultancy report, No. GH3811, to Directorate of Geohydrology, Dept of Water Affairs and Forestry, Pretoria.

Vegter J.R. (2000) Groundwater Development in South Africa and an Introduction to the hydrogeology of Groundwater Regions, Report No TT 134/00, Water Research Commission, Pretoria.

Weaver, J. 1992, *Groundwater Sampling*, WRC Project No 339, Pretoria

Woessner, W.W. 1998. Changing views of stream-groundwater interaction, Gambling with groundwater-physical, chemical, and biological aspects of aquifer-stream relations, Brahana *et al.*, (eds.) pp1-6, Copyright by the American Institute of Hydrology (AIH).

Xu, Y. Braune, E. Colvin, C. le Maitre, D. Pietersen K. and Hotom, T. 2000. "Comprehensive determination of resource directed measures for groundwater in South Africa", In Groundwater: Past Achievements and future challenges, Sililo *et al* (eds.), Balkema, Rotterdam (ISSN 905809 1597).

Xu, Y and van Tonder, GJ 2001. "Estimation of recharge using a revised CRD method", ISSN 0378-4738, Water SA, Vol.27 No. 3 July 2001.

Xu, Y, Mafanya T, van Tonder G. J. and Partridge T. 2001. Estimation of monthly groundwater discharge time series under simplified hydrogeological scenarios in South Africa. Tenth South African National Hydrology Symposium, University of Natal-Pietermaritzburg, available at http://www.beeh.unp.ac.za.

Zhang, J. 2000. Estimation of the Preliminary Groundwater Reserve Using Numerical Models, M.Sc. thesis, Institute for Groundwater Studies at the University of the Free State, Bloemfontein.