Groundwater Resource Directed Measures

July 2009

GRDM Training Manual

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PREFACE

This manual is a revision of the original manual produced by Parsons and Wentzel (2007). At the time of compiling the manual, no formal Classification system was in place. The Water Resource Classification System that was developed by Dollar et al (2006) forms the basis of the Classification System adapted in this manual. Since RQOs are dependant on Classification, they could also not be addressed formally.

The concepts of Classification and RQOs now receive the attention that is due to them. These processes are interlinked and cannot be treated independently. During the period that this manual has been in use, it has become apparent that the groundwater contribution to baseflow in rivers is probably much smaller than originally assumed. This has the implication that Classification becomes the mechanism that should be utilised in the RDM process to ensure that groundwater is used sustainably.

However, the original manual played a crucial role and many people were trained in the concepts and applicability of GRDM, albeit imperfect. The main aim of the Manual is to produce a methodology that is scientifically robust, yet easy to implement. It is accompanied by dedicated software that will take the user through all the required processes required by the NWA.

A word of warning, though. The software is very user friendly and in many instances it also provides a default value. The inherent danger in this is that people without the necessary geohydrological background could come up with answers that could be non-sensical. It is therefore imperative that the software only be used by people who have the required background to do so.

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LIST OF ABBREVIATIONS

BHN	Basic Human Needs
CMA	Catchment Management Agency
CMS	Catchment Management Strategy
CRD	Cumulative Rainfall Departure
DSS	Decision Support System
DW&EA	Department of Water and Environmental Affairs
EARTH	Extended Model for Aquifer Recharge and Soil Moisture Transport through the Saturated Hardrock
EC	Electrical Conductivity
EIS	Ecological Importance and Sensitivity
EMC	Ecological Management Category
ER	Ecological Reserve
EWR	Ecological Water Requirements
FETWater	Framework Programme for Education and Training in the Water Sector
GG	Government Gazette
GMU	Groundwater Management Unit
GRDM	Groundwater Resource Directed Measures
GRU	Groundwater Resource Unit
ICM	Integrated Catchment Management
IFR	Instream Flow Requirements
IGS	Institute for Groundwater Studies
IUAs	Integrated Unit of Analysis
IWRM	Integrated Water Resource Management
K	Hydraulic Conductivity
MAP	Mean Annual Precipitation
MAR	Mean Annual Runoff
MLF	Maintenance Low Flow
NGDB	National Groundwater Data Bas

NWA	National Water Act (Act 36 of 1998)
NWRS	National Water Resource Strategy
PES	Present Ecological State
PESC	Present Ecological State Category
RDM	Resource Directed Measures
RQO	Resource Quality Objectives
RU	Resource Unit
S	Storativity
SI	Stress Index
SANBI	South African National Biodiversity Institute
SAM	Strategic Adaptive Management
SDC	Source Directed Controls
T	Transmissivity
TMG	Table Mountain Group
WAP	Water Allocation Plan
WARMS	Water Use Authorisation and Registration Management System
WEM	Water Environment Management
WMA	Water Management Area
WMS	Water Management System
WRC	Water Research Commission
WRCS	Water Resources Classification System

UNITS OF MEASUREMENT

a	annum
cm	centimetre
d	day
ha	hectare
km^2	square kilometre
ℓ	litre
ℓ/pppd	litres per person per day
m	metre
Ma	million years
m^2	square metre
m^3	cubic metre
mamsl	metres above mean sea level
mbgl	metres below ground level
mbs	metres below sea level
MCM	million cubic metre
mg	milligram
mm	millimetre
mS/m	milliSiemen/metre
s	second

1 INTRODUCTION

Sustainability, equity and efficiency are identified as central guiding principles in the protection, use, development, conservation, management and control of water resources. These principles recognise the following:

- basic human needs of present and future generations,
- the need to protect water resources (for use),
- the need to share some water resources with other countries,
- the need to promote social and economic development through the use of water and
- the need to establish suitable institutions in order to achieve the purpose of the National Water Act (Act No. 36 of 1998) (NWA).

To be able to implement the NWA, the Minister needs to ensure that the tools and expertise required to implement the Act are available. This manual addresses the methods and procedures needed to implement RDM. It must be remembered that RDM forms the legal framework for establishing management plans and hence allocation schedules and licensing conditions pertaining to our water resources. Should the legal process not be in place, subsequent WAPs and licensing conditions could be challenged in court.

In essence, this manual is about the techniques to ensure that groundwater resources will be used in a sustainable way as prescribed by the NWA. This forms the cornerstone of the long-term sustainable use of the resource – the other two components being equity and efficiency. The three together address the concept of sustainable development within the principles of IWRM.

The underlying objective of resource protection as is envisaged in Chapter 3 of the NWA is to ensure that the integrity of the resource is not compromised. Classification defines the level of integrity to be maintained, Reserve addresses ecological integrity and RQOs gives guidance on how all the components of integrity can be achieved, based on both the Reserve as well as Classification.

1.1 Summary of the training manual

Chapter 2 sketches the historical background to water use in South Africa. It emphasises that historically, water was considered a “public good” but during the colonial period water rights became linked to property rights.

It also highlights the legislation that preceded the current NWA and the role that it played in drafting the NWA. Key aspects in the NWA as well as the issues that relate directly to groundwater are highlighted.

The foundations of water management are discussed in Chapter 3. Although rooted in the internationally accepted concept of IWRM, only the South African approach is discussed, namely the three basic pillars of sustainability, equity and efficiency.

Protection measures as contained in the NWA are highlighted with the emphasis on Resource Directed Measures (RDM), which is the precursor to water use authoristaion. Water use that is permissible under the NWA is listed and the components where groundwater is involved are highlighted.

Chapter 4 gives a broad overview of the RDM process as applied to groundwater. It also summarises the steps required during an assessment. Post RDM activities are briefly discussed to emphasize the role of RDM within the greater resource protection and management.

RDM assessments can also be undertaken at different levels of confidence and these are discussed in Chapter 5. Guidance is also provided in terms of assessing the most appropriate level for a particular study.

Chapter 6 focuses on the role that groundwater in other components of the water cycle and in particular baseflow in rivers, wetlands and other terrestrial ecosystems.

Chapter 7 forms the backbone of the manual. The steps proposed for a RDM assessment are discussed in detail.

Chapter 8 explains in detail methods, tools and data used in the RDM assessment. From the Reserve perspective, recharge and groundwater contribution to baseflow receive special attention. An approach to setting RQOs is also discussed in more detail.

Chapter 9 is an introduction to the software that accompanies the training manual. It gives an overview of the graphical interface and also discusses the system design. It ends by taking the reader through the road map to be followed during an assessment.

Key detail that has been changed in this revision is the approach to Classification and the concomitant RQOs. In stead of viewing the RDM process as different to any other hydrogeological assessment, emphasis is placed on the fact that the key element in all three aspects, namely Classification, Reserve and RQOs is the protection of System Integrity and that the three components just address them differently.

2 HISTORICAL OVERVIEW OF WATER USE IN SOUTH AFRICA.

There is no written history of water customs and use in South Africa prior to the arrival of European settlers in the 17th Century. The historical importance of water in culture from this period survived in the religious and cultural uses of water that are, even today, of significant importance. From these uses it can be surmised that water was regarded as a common good and that the concept of “private water” was alien in the traditional African sense. The traditional approaches showed great respect for water and regarded it as an indivisible link in the human cycle.

The early European settlers in Southern Africa settled in areas where water was in abundance and from early times South African law was based on the needs of these settlers to protect their domestic and agricultural needs. During the twentieth century it was expanded to include industrial needs.

Roman Dutch Law had a strong influence in shaping the South African Law. Later English Law also played a role, but to a lesser, but nonetheless important extent. A principle in Roman law was that all running water in public rivers is for the **common benefit** of all users (Kavin, 2000). These principles became part of South African Law in the early 19th century. During the occupation of the British during the 19th and 20th centuries, this concept was gradually changed and the streams and groundwater were regarded as belonging to the property where it occurs. The principles of riparian right were thus established. During the industrial revolution in the 19th century, this principle was further entrenched in various acts, such as the Cape Colony Irrigation Act (Act 32 of 1906) and the Transvaal Irrigation Act (Act 27 of 1908).

After the establishment of the Union of South Africa in 1910, these Acts were repealed and replaced by the Irrigation and Conservation of Waters Act (Act 8 of 1912). This Act focussed on the protection of irrigation rights and to a lesser extent the requirements of industry.” Subterranean water” was restricted to areas underlain by dolomites.

Due to the increase in demand from industry (especially mining) this Act was repealed and replaced by the 1956 Water Act (Act 54 of 1956).

This Act entrenched the concept that sole and exclusive use of private water vested in the owner of the land on which it was found. Underground water could only be conveyed beyond the boundaries of the property with the consent of the owner. However, the Act did make provision for the control of over-abstraction, use, supply and distribution of subterranean water by declaring an area a Subterranean Control

Area (Section 28 of Act 54 of 1956). To some extent this was this first partial return to Roman Dutch Law that prevailed during the 17th century (Kavin, 2000).

The reform in approach to the current Water Act saw its inception in 1992 in Rio de Janeiro. Agenda 21 prepared and adopted at the UN Conference on Environment and Development in Rio de Janeiro described Integrated Water Resource Management (IWRM) as a primary tool for the management of water resources and viewed the water resource as a unitary hydrological cycle. The relevant guiding principles were as follows:

- Ensure the integrated management and development of water resources
- Assess water quality, supply and demand
- Protect water resource quality and aquatic ecosystems
- Improve drinking water supply and sanitation

South Africa as a member state to the United Nations agreed to report on a regular basis on progress with the implementation of the Agenda 21 agreements and hence it became imperative that the Water Act be brought in line with the Agenda 21 agreements to achieve sustainable development on national, regional and local levels.

This must also be viewed from the angle of the Constitution of South Africa that states:

Everyone has the right to have access to sufficient food and water…

The State must take reasonable legislative and other measures, within its available resources, to achieve the progressive realisation of these rights

After 1994, one of the first tasks of the Minister of Water Affairs, Kader Asmal, was to bring the legalisation in line with these principles. The water legislation in South Africa was reviewed extensively to bring it in line with the Agenda 21 agreements and the global agenda for sustainable development[1].

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[1] *Sustainable development is defined as the integration of environmental concerns in social and economic development decision-making processes*)

Some policy documents and legislation pertaining to the NWA are the following:

2.1 The National Water Supply and Sanitation Policy (1994)

The Water Supply and Sanitation Policy determined to a large degree what followed. It was motivated by approximately 10 million people that did not have access to adequate water supply and a further 22 million without access to acceptable sanitation. The following principles emanated from this document:

► Development should be demand driven and community based

► Basic services are a human right

► The Resource should be utilised sustainably ("*Some for all, forever, together*")

► Equitable regional allocation

► Water has an economic value

► The user pays

► Integrated development

► Environmental integrity

The scene was now set for a fundamentally different approach to our water resources, namely, as a first priority, to supply water to people in a sustainable developmental way. These rights were further enshrined through the adoption of a Bill of Rights that states:

"Everyone has the right to have access to sufficient food and water.

Everyone has the right to an environment that is not harmful to their health and well-being.

Everyone has the right to an environment protected, for the benefit of present and future generations, through legislative and other measures that

► *prevents pollution and ecological degradation*

► *promotes conservation*

► *secures ecologically sustainable development and use of natural resources while promoting justifiable economic and social development."*

2.2 The Water Services Act (Act 108 of 1997)

The National Water Supply and Sanitation Policy culminated in the publication of the Water Services Act in 1997and was primarily aimed at regulating the domestic needs of millions of people who had no water services at that stage. The WSA main aim is to regulate water services institutions like water service providers and other bodies prescribed in the WSA. It is proposed that catchment management strategies include groundwater specifically, as spelled out in the NWRS, to ensure groundwater is integrated into a catchment's water resources management.

Important from the perspective of RDM is to recognise that the outcomes of the RDM process should assist the allocation schedules required by the water service providers and hence make the important link between resource use and resource management within a properly defined legal framework.

2.3 The National Water Policy

The National Water Policy was published in 1997 and was based on 28 Fundamental Principles and Objectives for a new South African Water Law. The salient points are summarised as follows:

Legal aspects

- the water law shall be consistent with the Constitution and will actively promote the values enshrined in the Bill of Rights
- all water shall have a consistent status in law, irrespective of where it occurs
- there shall be no ownership of but only a right (for the environment and basic human needs) and an authorisation to use water for all other water users. No authorisation shall be in perpetuity.
- the riparian principle shall not apply and it is a resource common to all.

The water cycle

- the unity of the water cycle and the interdependence of its elements are recognised.
- the basic hydrological unit is the quaternary catchment
- the variable, uneven and unpredictable distribution (spatially and temporally) should be acknowledged.

Water Resource Management Priorities

- ► management objectives are to achieve optimum long term, environmentally sustainable, social and economic benefit for society from their use.
- ► water required by people shall be reserved.
- ► ecological functions of water required for human use shall be maintained to ensure that the quantity, quality and reliability not be compromised.
- ► allocations for downstream countries shall be respected

2.4 The National Water Act (Act 36 of 1998)

The NWA does away with previous concepts and establishes new principles with far reaching effects:

The distinction between public water, private water, normal flow and surplus flow is done away with. All water now has the same status.

The Minister of Water Affairs and Forestry is the public trustee of the nations' water resources. The Minister has the duty to

"*ensure that the water is protected, used, developed, conserved, managed and controlled in a sustainable and equitable manner for the benefit of all persons*".

The Minister is responsible for ensuring that the water is allocated equitably and beneficially in the public interest, while promoting environmental values (section 18 of the NWA). There is now no ownership of water, only an entitlement to it.

All new entitlements to use water are derived from the NWA. Once a water use authorisation is issued, it replaces all previous entitlements.

The unity and interdependence of the water cycle are recognised.

The only right to water is for basic human needs and to sustain the ecology

The riparian principle and private ownership of water have been discarded *in toto.* Therefore the licensing authority can grant a water use authorisation to a person on water found underground on land not owned or occupied by that person **if there is good reason to do so.**

The right to use water is spelled out in Section 22 of the NWA and can be summarised as follows:

- It is permissible under Schedule 1
- It is permissible as a continuation of an existing lawful use
- It is permissible in terms of a general authorisation
- It is permissible when a water use authorisation has been issued.

The process that must be followed before a water use authorisation can be issued is spelled out in Chapter 3 of the NWA and is collectively referred to as Resource Directed Measures.

Any resource must be assessed in terms of:

- Classification
- Reserve
- Resource Quality Objectives

The class of a resource sets the background in terms of the level of protection that must be maintained for a particular resource. The Reserve, which is based on Classification, quantifies the amount of water that must be set aside for basic human needs and to ensure that EWR can be met as specified in the Classification. RQOs, which is based on Reserve and Classification, spells out objectives how to attain these protection measures.

The NWA clearly includes groundwater in a unitary hydrological cycle and in the definition of a water resource, but the characteristics of groundwater sometimes require it to be considered or managed differently to other water resources. This concept will be discussed in detail in later chapters.

3 FOUNDATIONS OF WATER MANAGEMENT IN SOUTH AFRICA

The Integrated Water Reform Process, which is our ultimate aim, is very encompassing and must consider processes that occur outside the strict definition of the water environment. It has to adhere to international standards and conventions, but the outcome should ensure that our resources are used sustainably on a local as well as a regional scale. (Fig 3.1).

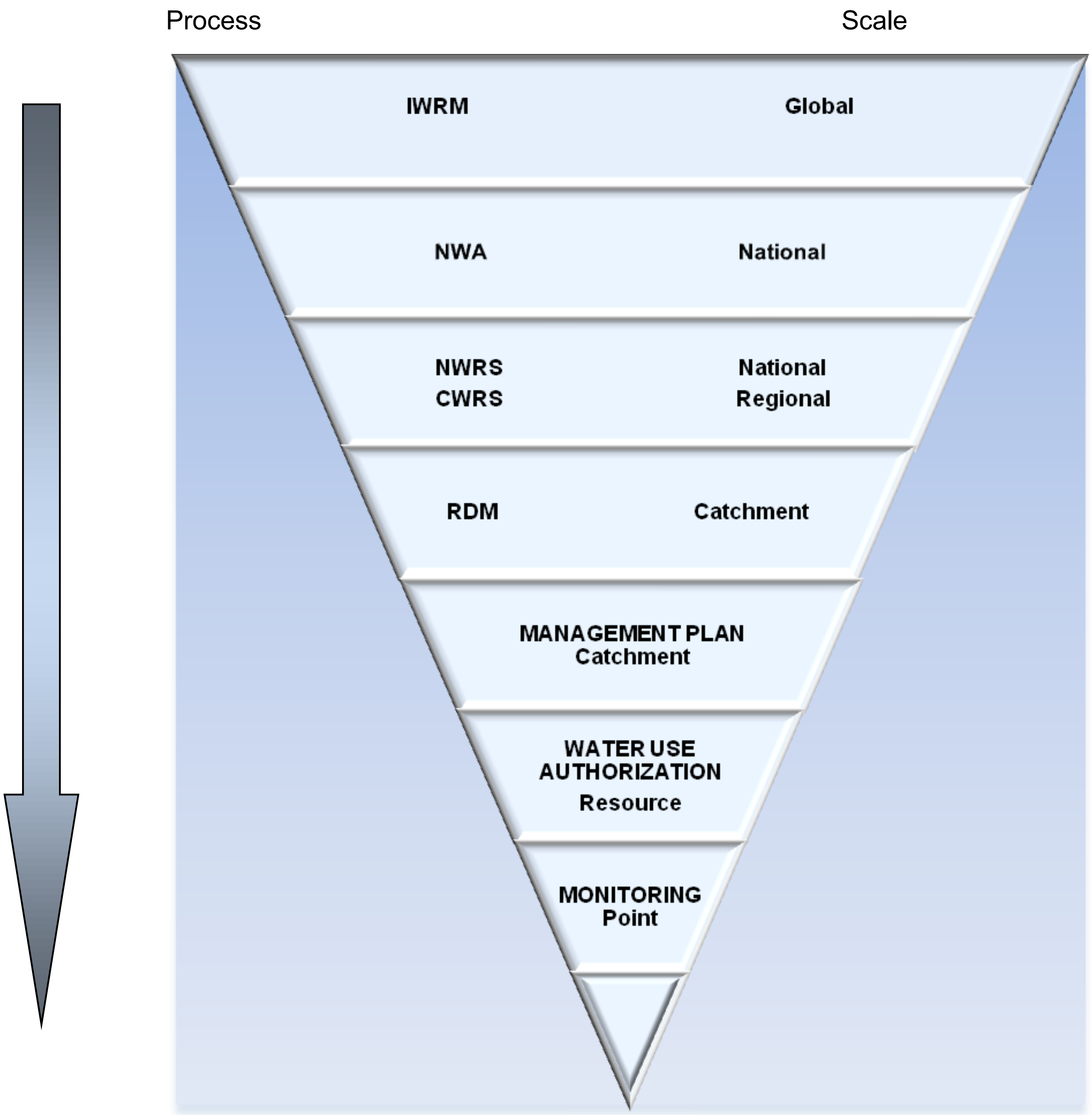


Figure 3.1 Diagrammatic representation of the Integrated Water Reform Process

The Constitution is the highest law of the land, and all other laws must be aligned with it. As a result, the Constitution and Agenda 21 (which is an international plan for sustainable development to which South Africa is a signatory) formed the basis for water management in South Africa. To implement water policy, two new acts were drafted and signed into law:

National Water Act (Act No. 36 of 1998): This Act deals with the management of water resources, and its purpose is to ensure that there will be water for basic human needs and for the economic development of the country. The NWA recognises the interdependency of all the components of the water cycle and that these should be managed as a single resource.

Water Services Act (Act No. 108 of 1997): This Act provides the right to access to basic water supply and sanitation and provides the framework for delivery of these water services to the people of the country.

These two Acts complement each other and must be treated by DW&EA as such.

Water is a natural resource and belongs to all the people of South Africa. The Department of Water and Environmental Affairs (DW&EA) has the responsibility of managing water resources on behalf of the people of South Africa. In order to achieve this, a National Water Resource Strategy (NWRS) was developed. The strategy describes the ways in which all water resources will be protected, used, developed, conserved, managed and controlled. This long-term plan is to be reviewed every five years.

This manual focuses on Chapter 3 (sections 12–18) of the NWA, which deals with the protection of water resources. This includes

- Classification,
- Reserve and
- Resource Quality Objectives,

collectively referred to as Resource Directed Measures or RDM.

To distinguish between RDM in general and RDM related to groundwater, the term Groundwater Resource Directed Measures (GRDM) will be used when the focus is only on groundwater. It is important to note that the focus in this manual is on the sustainability aspects of GRDM and that social and economic considerations will be addressed in CMS, allocation schedules and licensing conditions.

> *"Everybody has the right to an environment not harmful to their health and well-being, to have an environment protected for the benefit of present and future generations, and to have access to sufficient food and water".*
>
> Constitution of the Republic of South Africa (Act No. 108 of 1996)

3.1 Fundamental principles of water management in South Africa

The main responsibility of DW&EA is to ensure that sufficient water of an acceptable quality is available to meet basic human needs, meet ecological water requirements and to support economic and social development. South Africa is not a water-rich country and, as a result, water has to be managed and used wisely. Water management in South Africa is based on three key principles:

- **Sustainability** – water use must promote social and economic development, but not at the expense of sustaining the environment (technical component).
- **Equity** – every citizen of the country must have access to water and the benefit of using water (social component).
- **Efficiency** – water must not be wasted and must be used to the best possible social and economic advantage (economic component).

The NWA requires water management strategies be addressed at both national and catchment level. A National Water Resource Strategy (NWRS) was developed as a framework for managing water resources in the country. WMAs need to develop CMS which take the local conditions into account but is still not in conflict with the NWRS. The draft CMS will primarily be based on the outcome of the RDM process that should give guidance to sustainable use of the resource as well as the ISP for the catchment, but will rely heavily on stakeholder input for finalisation.

The NWA requires a balance between use and protection. While it is desirable that we do not impact on our water resources, it is also desirable that we have economic growth and address poverty in the country. Some impact is hence inevitable. The NWRS aims to provide a framework in which this balance can be attained. However, the aim is always to limit the impact in such a way that the long term sustainable use of the resource is not compromised.

South Africa has been divided into 19 Water Management Areas (WMA) (Figure 3.2). These WMAs will be managed by catchment management agencies (CMAs), which will be responsible for implementing the NWRS as well as catchment-specific strategies. The CMS must be in harmony with the NWRS (DW&EA, 2007). It is currently envisaged that there will be nine CMAs, but still 19 WMAs.

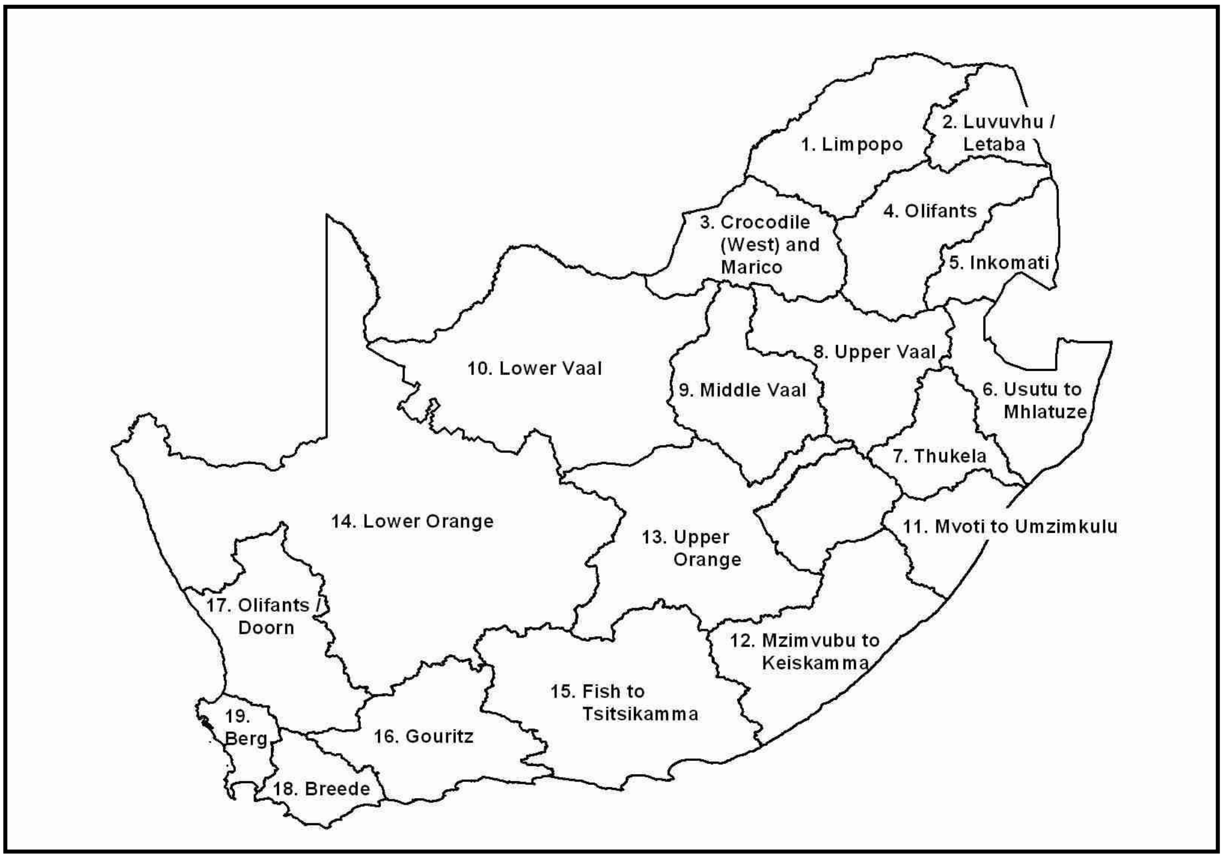


Figure 3.2: National scale map of water management areas in South Africa

3.2 Protection of water resources

Chapter 3 of the NWA provides a legal framework for attaining a balance between protecting and using water resources. These include:

- Classification of water resources
- The Reserve
- Resource Quality Objectives
- Source-directed controls (pollution prevention and remediation)
- Emergency incidents.

The first three are described as RDM. These address the quantity and quality of water in a water resource as well as the fauna and flora dependant on the resource. Those approaches that target the control of impacts that result (or could result) from the use of a water resource or adjacent areas are described as source-directed controls (SDCs). SDCs typically aim to control and manage pollution (disposal of effluents) and over-use of water resources (abstraction of water). Water quality issues are normally only addressed through SDCs. Though these two controlling mechanisms are interlinked and have a degree of overlap, this manual focuses on RDM. The overall water resource management business process envisaged by DW&EA (1999) has been adapted and is illustrated in Figure 3.3.

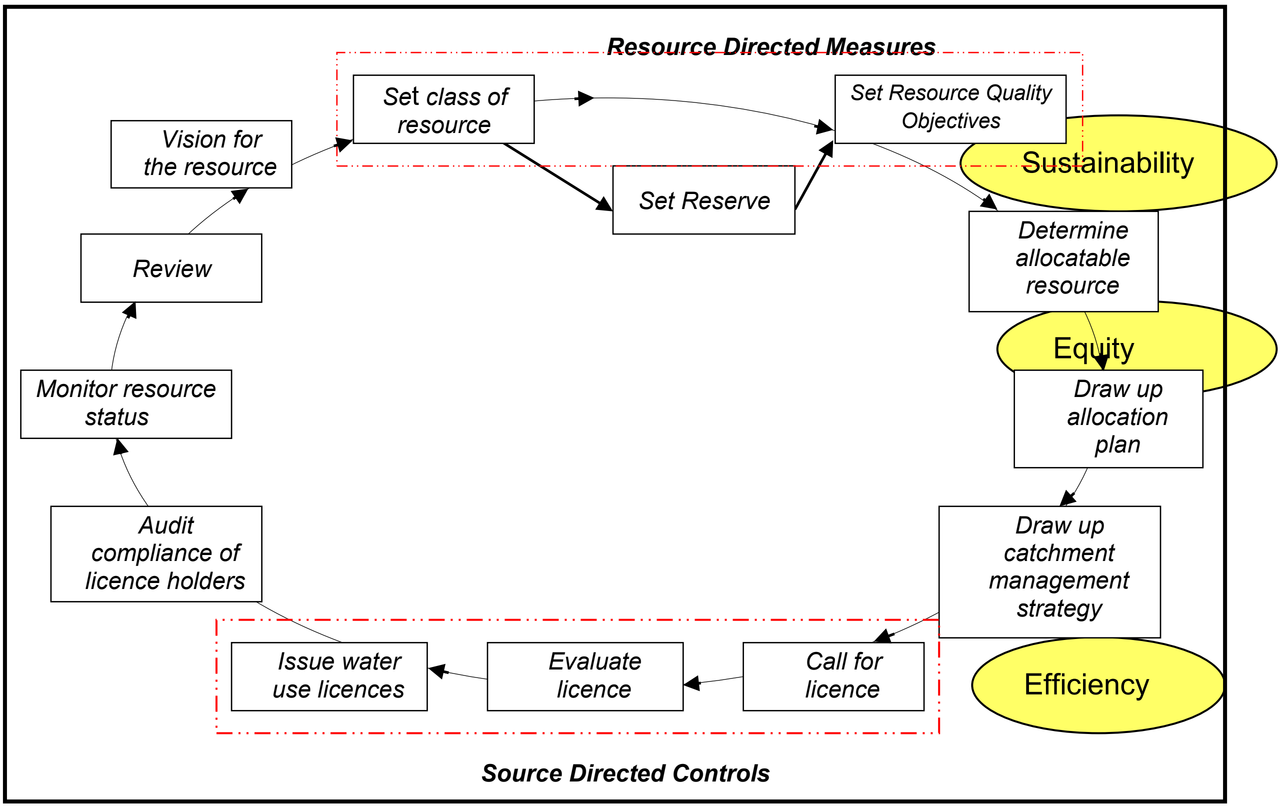


Figure 3.3

Because of the physical differences between surface and groundwater, this manual specifically focuses on RDM related to groundwater. These are abbreviated as GRDM. The wide geographic extent and slow rate of movement are just two of the characteristics of groundwater that make it significantly different from surface water bodies. Groundwater is not afforded sufficient protection under the Reserve, particularly in those areas where the resource has no apparent link to surface water. In these areas, Classification and Resource Quality Objectives are the mechanisms used to ensure the sustainable use of the resource, as dictated by the NWA.

3.3 Water use

The NWA requires all water use to be authorised. This tool aims to promote the wise use of water. Before any water use can be authorised, water has to be set aside for Classification, the Reserve, international obligations, inter-basin transfers, strategic use and future use. These allocations are to be done at a national level by DW&EA. CMAs are responsible for authorising and allocating the balance of the water resource at a catchment level.

Four main mechanisms for authorising water use have been established. It is recognised that the biggest water users have the biggest risk impacting negatively on water resources. Moreover, DW&EA does not have sufficient resources to authorise all water use. To overcome this problem, various mechanisms of authorisation were developed (Figure 3.4):

► Schedule 1 Use – the NWA automatically authorises users who use small amounts of water for household use, watering gardens and animals (not for commercial purposes) and storing or using rainwater from a roof to do so. No limit is specified for Schedule 1 Use.

► General Authorisation – in terms of section 39 of the NWA, users may use water without a licence provided the water use is within the conditions of the GAs. The GAs were first published in the *Government Gazette* of 8 October 1999 (GG No. 20526 Notice 1191). However, a revised GA was published on 27 February 2004. In terms of the GA, water users must still register their use, but need not apply for a licence.

► Continuation of Existing Lawful Use – any lawful water use under any law passed between 1 October 1996 and 31 September 1998 can continue, until such users are licensed.

► Water use authorisation (Licensing) – All water users who fall outside these definitions require a licence. A licence entitles a water user to use water within the conditions of the licence. These conditions must be reviewed every five years and a licence may only be issued for a maximum of 40 years.

In instances where there is not enough water for all users and the water resource is considered stressed, e.g. water use (or demand) is greater than the volume of water available, a process of compulsory licensing will be invoked. This could result in the withdrawal of generally authorised use and continuation of existing lawful use. All water users – excluding Schedule 1 users – will then have to apply for a licence.

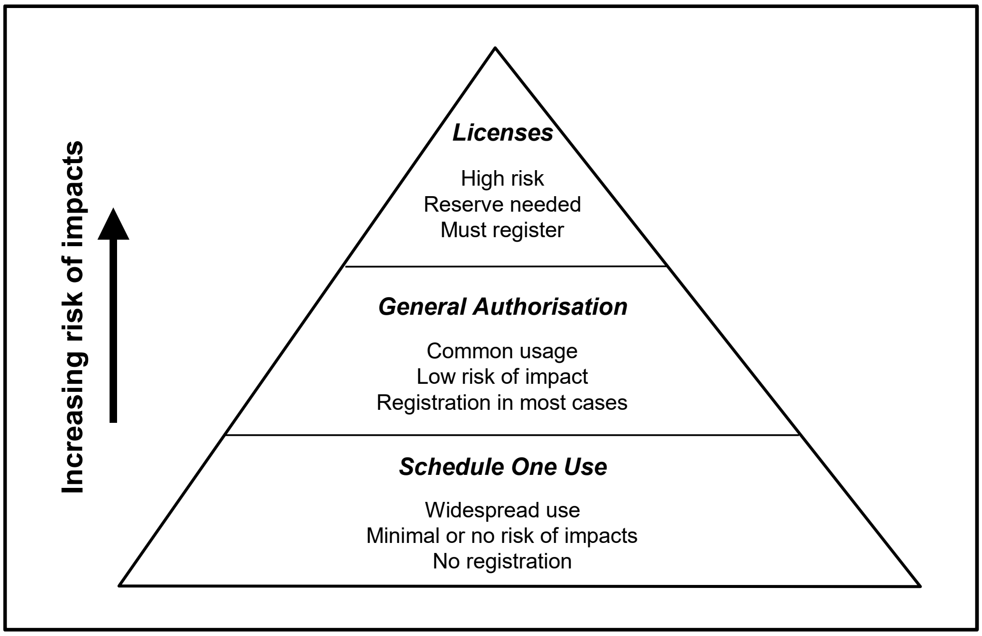


Figure 3.4: Schematic representation of mechanisms used to regulate the use of water

From the National Water Act: Definition of Water Use

Under Section 21 of the National Water Act (Act No. 36 of 1998), water use includes:

taking water from a water resource;

storing water;

impeding or diverting the flow of water in a watercourse;

engaging in a stream flow reduction activity contemplated in section 36;

engaging in a controlled activity identified as such in section 37(1) or declared under section 38(1);

discharging waste or water containing waste into a water resource through a pipe, canal, sewer, sea outfall or other conduit;

disposing of waste in a manner which may detrimentally impact on a water resource;

disposing in any manner of water which contains waste from, or which has been heated in, any industrial or power generation process;

altering the bed, banks, course or characteristics of a watercourse;

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

using water for recreational purposes.

*Note: Water uses in **bold** relate directly to groundwater.*

3.4 Management and monitoring

The Minister of W&EAs is the public trustee of water resources and has the overall responsibility for all aspects of water management. However, responsibility as well as authority for water management will eventually be devolved to a local level. It is planned that DW&EA will ultimately provide national policy and a regulatory framework for water resource management, and will make sure that other water institutions are effective. It is expected that the Department will still be responsible for RDM assessments, for example, while CMAs will be responsible for allocating available water resources, managing the allocation process and monitoring both water use and resource response to that use.

Monitoring and monitoring information systems form a crucial part of the management of the country's water resources. It is a requirement of the NWA that the Minister must establish a national monitoring programme:

> (*1) "The Minister must, as soon as reasonably practicable, establish national information systems regarding water resources.*
>
> *(2) The information systems may include, among others -*
>
> *(c) a groundwater information system"*

Extensive monitoring already takes place, but both surface and groundwater monitoring programmes need to be extended. Similarly, the information systems used to capture monitored data also need to be revised and updated on a regular basis. It is not stipulated that DW&EA should do all the monitoring themselves; hence it is assumed that other sources of data can be incorporated in the information system. The GRIP programme has already gone a long way to achieve this objective.

3.5 In summary

The NWA aims to ensure access to a limited resource on an equitable basis in an integrated, manageable and sustainable manner. The NWA moves away from riparian and property rights, but recognises basic human needs and water needs to sustain the environment. The promulgation of the NWA has resulted in significant changes in the way in which we use and manage water. Because of the shift from private to public water, this is particularly true of the groundwater component of the hydrological system that was previously regarded as private.

4 INTRODUCTION TO RESOURCE DIRECTED MEASURES

4.1 Overall process

The objective of RDM is to facilitate the proactive protection (for use) of the country's water resources, in line with sustainability principles. The NWA recognises the need to develop and use the country's water resources for growth. However, the NWA also recognises that our water resources must not be used to the detriment of future users. RDM hence strives to ensure that the water resources are afforded a level of protection that will assure a sustainable level of development that would guarantee future use. To this end, RDM comprises three main interrelated components, namely:

- Classification
- Reserve
- Resource Quality Objectives.

The relative importance of the three components of the protection of groundwater resources was discussed in Chapter 2. Sequential steps to be followed when assessing these three components are illustrated in Figure 3.5, and are briefly described in this chapter. Detailed discussions are presented in Chapters 6–11.

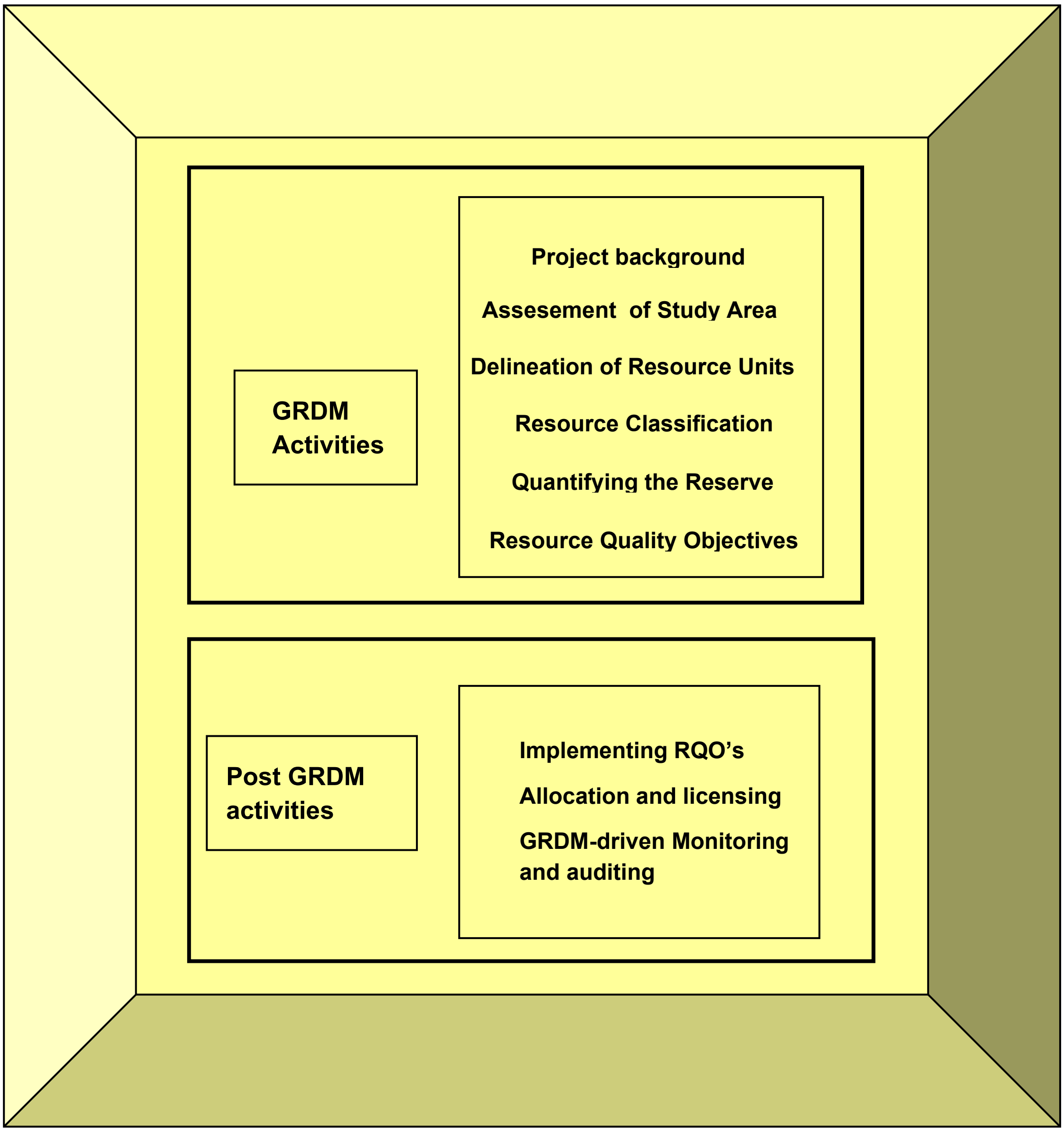


Figure 3.5: Sequential process of GRDM studies

The NWA is implemented in a phased approach and therefore the process is dynamic. The aim of this manual is to reflect the latest understanding of the GRDM process and aims to standardise the approach. An extensive groundwater dictionary is included in the accompanying software to give guidance regarding groundwater and GRDM terminology.

4.2 Assumptions related to GRDM

To be able to undertake GRDM assessments and quantify the volume of groundwater required to meet Classification requirements and to sustain the Reserve, a number of assumptions are made:

- Groundwater systems are generally resilient and can normally recover from most perturbations. However, it is accepted that groundwater contamination can persist over decades and centuries.
- The ability of a geohydrological system to satisfy basic human needs, RQOs and the ecological Reserve is not impacted if regional groundwater levels do not decline significantly over the long-term and ambient groundwater quality remains within natural limits.
- The sustainable rate at which groundwater can be abstracted is a function of the average long-term annual recharge, while the volume of groundwater held in storage acts as a buffer during dry periods.
- It is assumed that recharge and groundwater abstraction are distributed relatively evenly throughout significant water resources.

The GRDM assessment will be carried out by persons qualified and experienced in the field of groundwater hydrology who, in turn, will collaborate with other specialist hydrologists and ecologists.

4.3 Introduction to the steps in undertaking a GRDM assessment

The GRDM methodology has grouped together activities that have a key outcome. This approach is simple, logical and easy to implement. This manual focuses on the sustainability components that have to be addressed by the groundwater specialist of the GRDM project team and does not address social or economic issues. It is recognised that the latter is a crucial component when the GRDM outcomes must be implemented, but the present aim is to first stabilise the technical approach to GRDM. A brief summary of the GRDM process is presented below and discussed in more detail in Chapters 6–11.

The key driver in this whole process is sustainability. If the resource is pushed beyond its sustainable limit, it is most likely that the social and economic objectives will also not be met.

4.3.1 Project Background and Objectives

Who	DW&EA RDM Scoping Team, which is to include a hydrologist, geohydrologist and ecologist
Purpose	To initiate a GRDM study Set the objectives Set the level of GRDM assessment required Appoint a GRDM assessment team

How	Using expert knowledge of the water resources of an area and an understanding of local management issues Desktop GRDM assessment using the GRDM software
Key Outcomes	Map defining the area to be studied Selection of the level of GRDM assessment required Project Terms of Reference Appointment of a project team to undertake the assessment

4.3.2 Assessment of the study area

Who	Project geohydrologist, with input from other specialists when required
Purpose	To describe the study area in terms of its physiographic and geohydrological characteristics with emphasis on resource integrity in detail appropriate to the level of GRDM assessment required
How	This is essentially a data gathering and analysis phase, typical of any geohydrological resource assessment. Approaches, methods and tools typically used in geohydrological assessments are used.
Key Outcomes	Geohydrological report of the area, including maps and tables, documenting characteristics such as climate, topography, drainage, geology, geohydrology, groundwater use, surface–groundwater interaction, groundwater-dependent ecosystems etc.

4.3.3 Delineation of resource units

Dollar et al (2006) brought in the concept of an Integrated Unit of Analysis (IUAs) that refers to an area where linkages with other components take place.

Who	Project geohydrologist, with input from other specialists when required
Purpose	Delineate groundwater resource unit (or IUAs) based on quaternary catchment boundaries, aquifer type (primary aquifer, secondary aquifer, dolomitic aquifer) and other physical, management and/or functional criteria
How	Quaternary catchments form the basic unit for a GRDM assessment. These units can be further subdivided (or grouped). Links to other components of the water resource must be clearly defined. The final IUA, if not the quaternary catchment, must clearly indicate these links.
Key Outcomes	Map showing the extent of the groundwater resource units. GRDM assessment data sheet, in which the name of each unit and its aerial extent are recorded

4.3.4 Resource Classification

Who	Project geohydrologist, with input from other specialists when required
Purpose	To define the current classification of each groundwater resource units (IUAs) using the prescribed classification system, the output of which will feed into processes for setting desired management classes for the relevant IUAs.
How	Using the concept of a Stress Index for quantity and quality, the present water resource classification of each IUAs is determined. It is based on both quantifiable and non-quantified parameters, as well as expert judgment.
Key outcomes	Classification of each groundwater resource units (IUAs) (minimally impacted, moderately impacted, heavily impacted).

4.3.5 Quantification of the Reserve

Who	Project geohydrologists, with support from the hydrologist
Purpose	To quantify the volume of groundwater that can be abstracted from a groundwater resource unit without impacting the ability of the groundwater system to contribute to the Reserve (basic human needs, EWRs dependent on groundwater)
How	Quantify recharge to the groundwater resource unit, using appropriate methods Quantify the groundwater contribution to EWRs, using appropriate methods Quantify the basic human needs of the unit to be met from groundwater
Key outcomes	Calculation of the Reserve as a percentage of recharge

4.3.6 Setting Resource Quality Objectives

Who	Project Geohydrologist, aquatic ecologist
Purpose	Set RQOs for each IUAs using rules for selected classes
How	Based on the conceptual understanding of the area and factors that could affect the Resource Integrety, select key measurable indicators as RQOs (e.g. water levels, TDS, fecal coliforms, etc) and the level at which they should be maintained on a catchment level.
Key outcomes	List of RQOs to guide management and monitoring activities.

4.4 Post-GRDM assessment activities

Setting RQOs marks the completion of the technically driven components of the GRDM process. However, the process is not only technically based. It must also consider social, economic, efficiency and other factors. This is mainly the function of the CMA. Because of this, the process must feed into the catchment visioning process and demarcated the linkages to other components of the hydrological cycle that may have emerged during the GRDM assessment. In addition, once the GRDM assessment is in place, monitoring requirements and allocation of the water resource has to be considered.

4.4.1 Implementing Resource Quality Objectives

RQOs in essence will ensure the sustainable use of the Resource. The two other principles of the NWRS - namely equity and efficiency - also need to be addressed by the CMA before allocation can be initiated.

It must be borne in mind that RQOs are catchment based goals but the information supplied by the groundwater specialist during the GRDM process should be quantified during the water allocation and licensing processes.

4.4.2 GRDM-driven monitoring

Monitoring essentially falls outside the GRDM process, but is required to ensure that RQOs are realistic and are adhered to. Information obtained from post-GRDM assessment monitoring will be used in the review of the assessment (usually within a period of five years). Monitoring forms an essential part of what must be a seamless process of managing the country's water resources. Guidelines regarding GRDM-driven monitoring and how it fits in the broader process of groundwater monitoring in South Africa are currently lacking.

It also plays a very crucial role in the long term since spatial and temporal datasets must be created that would guide the process in future and hopefully lead to more informed decisions when allocation plans are considered.

Three levels of groundwater monitoring are required by the GRDM assessment process:

► **National level** monitoring is the responsibility of central government (DW&EA) and aims to provide a national perspective on the status of groundwater resources for planning and management purposes. It provides information pertaining to background conditions required for assessing the state of groundwater resource units. A national groundwater monitoring programme is currently in place and comprises some 400 monitoring stations.

► **Regional level** monitoring could be described as catchment scale monitoring, and will typically be the responsibility of CMAs. This level represents the most suitable platform for monitoring within the context of GRDM, since it provides a synthesis of groundwater resource status and trends at a scale more appropriate for implementing meaningful resource management measures, standards and regulations. This will also ensure that the goals envisioned by the groundwater RQOs for the catchment are adhered to.

► **Local level** monitoring is site- and use-specific. This is the level at which the CMA should assess compliance with licensing conditions that emanated from the RQOs set for the catchment. Examples are monitoring at waste disposal sites and water level monitoring around production boreholes.

4.4.3 Allocation

A GRDM assessment is only the start of the water resource management process and aims to determine the total amount of groundwater in a significant water resource and the amount that can theoretically be abstracted sustainably without impacting the ability of groundwater to support the Reserve and comply with Classification requirements. No attempt is made at this stage to apportion or allocate water to individual users or applicants. This occurs in a subsequent process that is not addressed in this training manual. It is, however, crucial that the GRDM outcomes be of such a nature that it will guide this process from a technical perspective.

4.5 Responsibilities of stakeholders within DW&EA

By definition GRDM is a legal process that must be driven by DW&EA. It is their responsibility to ensure that all impacts relate to sustainability on a particular resource is considered such as possible interaction with wetlands. They must ensure that the project team is qualified to address all relevant issues. However, there is no legal reason why a person outside DW&EA cannot initiate a RDM study. It must just be clearly understood that only DW&EA can give it legal status before it can be implemented.

4.6 In summary

GRDM comprises six sequential phases of investigation, including Classification, Reserve determination and setting RQOs. It forms part of the water management process in South Africa required by the NWA. GRDM focuses on the principles of sustainability, while equity and efficiency are addressed at CMA level. Because of groundwater’s unique characteristics, methods of assessment are somewhat different from other components of the hydrological system (rivers, wetlands, estuaries), but it is crucial that GRDM assessments be undertaken in an integrated manner.

5 LEVELS OF GRDM DETERMINATION

5.1 Introduction

Ideally, all water resources in South Africa should be assessed to the same degree and the results of the assessment should be of a high confidence. At present, the country does not have the manpower or financial resources to carry out GRDM assessments countrywide at a high level of confidence in the short term. To overcome this problem and in line with a differentiated approach adopted by DW&EA (2000), three strategies are followed:

- Priority areas are being identified that require detail investigation
- Different levels of GRDM assessments are being used.
- A multi-level approach can be applied in the same Resource Unit.

Four levels of GRDM determination are recognised, with each expected to yield a greater level of confidence in the results. However, it must be noted that data availability will dictate the confidence level. The following general features characterise the differences between the four levels:

Desktop: these determinations are done using readily available data and information; extrapolate the results from previous more detailed and localised assessments; have low intensity information requirements; take a matter of hours to complete; and yield results of very low confidence; usually the first step in any GRDM process and a useful planning tool. The software accompanying this Manual can greatly aid this process.

Rapid: similar to desktop determinations but include a short field trip to assess present conditions; typically used to assess individual licence applications with low impact, in unstressed catchments and/or catchments of low ecological importance and sensitivity and integrity requirements. It should take less than two weeks to complete.

Intermediate: these determinations yield results of medium confidence; require field investigations by experienced specialists and should take about two months (but <6 months) to complete; used to assess implications of individual licences of moderate impacts in relatively stressed catchments.

Comprehensive: comprehensive GRDM determinations aim to produce high confidence results and are based on site-specific data collected by a team of specialists; used for all compulsory licensing exercises, as well as for individual licence applications that could have a large impact in any catchment, or a relatively small impact in ecologically important and sensitive catchments. It should take less than two years to complete. Due to lack of long-term geohydrological data sets, GRDM assessments will only rarely be done at this level.

Provision is made in the GRDM software for a multilevel approach in a particular Resource Unit. This is applicable where only certain areas of the Resource Unit need to be assessed at a high level of confidence while the rest can be assessed at a lower level.

In essence, the **same method and approach** is used to undertake all GRDM assessments. The chief difference between the different levels of assessments is the nature and extent of data available for in use in the assessment.

In accordance with the **precautionary principle**, lower-confidence assessments need to be more conservative in nature than higher-confidence assessments. The level of confidence required depends on:

- The degree to which groundwater in the catchment is already used
- The ecological sensitivity and importance of the catchment
- The nature, extent and probable impacts of the water uses for which a GRDM assessment is being undertaken.

In practice, it has been found that the method of determination used does not necessarily coincide with the level of confidence of the results obtained. For example, in instances where good baseline data sets exist with which to define biophysical relationships, then a short-duration rapid assessment can produce results of high confidence. Similarly, in instances with poor historical data, low confidence results will be obtained – irrespective of the time and cost of study. It is hence incorrect to assume that the degree of confidence in the results would increase is in direct proportion to the time and cost of the study.

5.2 Guides for setting the level of GRDM determination

Accepting that DW&EA does not have the time or resources to undertake comprehensive GRDM assessments of each significant water resource, a hierarchical approach is required. Lower levels of confidence can be accepted in unstressed catchments, in catchments where the impact of groundwater use is low or in catchments where groundwater plays a limited role in sustaining the EWRs. Conversely, high levels of confidence are required in stressed catchments, ecologically sensitive or important catchments or where groundwater abstraction is known to be having significant negative regional impacts.

At present, no formal methods exist to guide the level of GRDM determination that is required. Xu et al. (2003) and Colvin et al. (2003) presented generic guides for setting the level of GRDM required, based on aquifer type, dependency and impact (Table 4.1). DW&EA (2003) presented a similar guide, but based on only stress and impact (Figure 4.1). This approach requires that the level of stress of a significant water resource be assessed as well as the potential impact of water use or proposed water use.

Table 4.1: Guide for setting the level of GRDM assessment required

Indicator	**Aquifer Type**		
	Low Yielding	**Moderate Yielding**	**High Yielding**
Sole source dependency	Intermediate	Comprehensive	Comprehensive
Highly impacted	Intermediate	Comprehensive	Comprehensive
High risk of contamination / over-abstraction	Rapid	Intermediate	Comprehensive
Moderately impacted	Rapid	Intermediate	Intermediate
Moderate risk of contamination / over-abstraction	Rapid	Intermediate	Intermediate
No sole source dependency	Rapid	Rapid	Intermediate
Low level of impact	Rapid	Rapid	Intermediate
Low risk of contamination / over-abstraction	Rapid	Rapid	Intermediate

Notes:

- Low yielding – harvest potential less than 10 000 m^3/km^2·a or average borehole yield less than 1 ℓ/s
- Moderately yielding – harvest potential between 10 000 and 50 000 m^3/km^2/a or average borehole yield between 1 and 2 ℓ/s
- High yielding – harvest potential greater than 50 000 m^3/km^2·a or average borehole yield greater than 2 ℓ/s

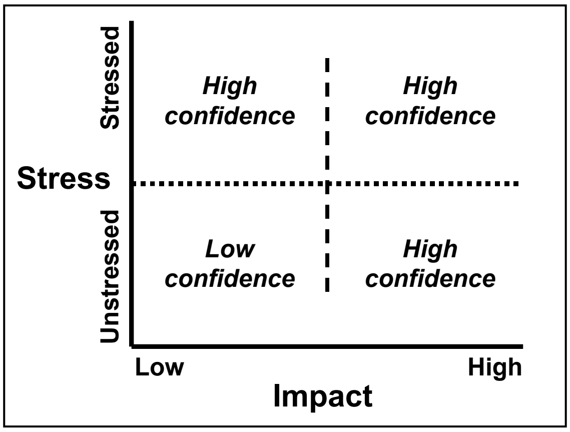


Figure 4.1: Level of confidence required for a GRDM assessment based on stress and impact (DW&EA, 2003).

The term 'water stress' is used in the National Water Act and by the GRDM fraternity, but has not been properly defined. The European Environmental Agency (as quoted by DW&EA, 2003) defines water stress as "*that which occurs when the demand for water exceeds the available amount during certain periods or when poor quality restricts its use*". Compulsory licensing has to be undertaken in areas of water stress, while it is generally accepted that higher-confidence GRDM assessments are required in areas of greater water stress. A number of indicators can be used to assess the level of stress of a groundwater system:

- Groundwater level – a decreasing or downward trend in groundwater levels
- Groundwater quality – a deterioration of groundwater quality – as indicated by an increasing or upward trend in chemical concentrations of typical contamination indicators such as EC, K, P, N and others
- Groundwater use – an increase in groundwater use within a catchment
- Disputes – an increase in the number of legal cases or disputes around groundwater use
- Boreholes – an increase in the number of boreholes within a catchment or an increase in the number of boreholes drying up
- Ecosystems – collapse of groundwater-dependent ecosystems, including springs and wetlands, or a reduction in baseflow
- System Integrity
- Pollution sources – an increase in the number of potential groundwater pollution sources, for example mining and industry.

The groundwater level in a stressed aquifer may behave in a manner similar to that displayed in Figure 4.2. Unfortunately, this sort of information is seldom available. Furthermore, the degree of stress is gauged by determining the Stress Index during the Classification process or by setting RQOs that would alleviate stress levels (see Chapter 9). These comparisons are only possible later in the GRDM process, while the level of confidence needs to be addressed at the outset.

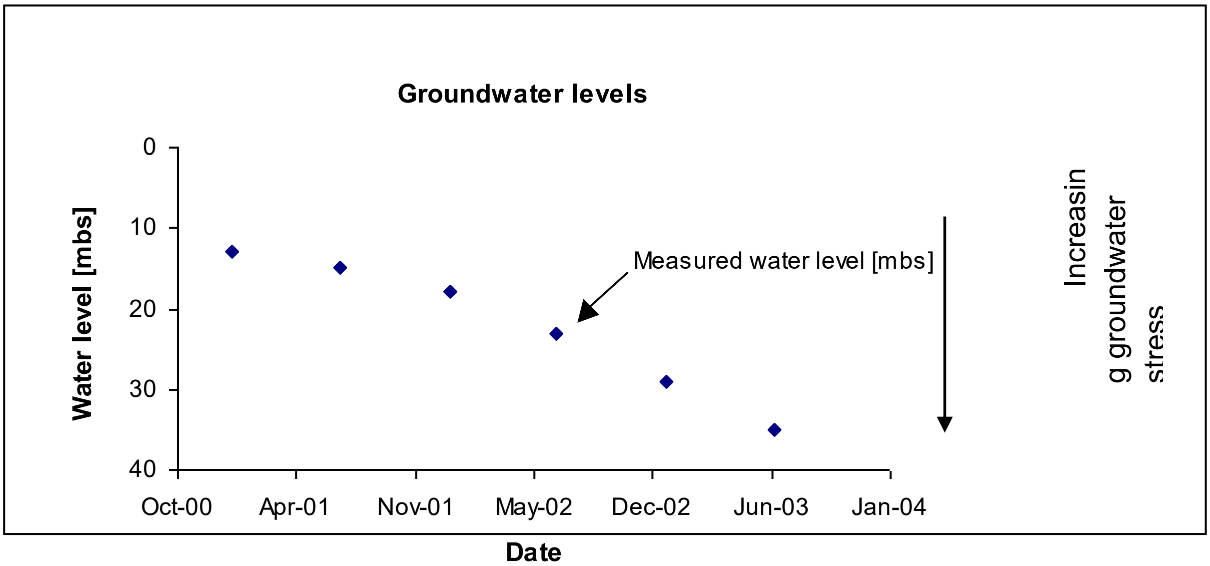


Figure 4.2: Using monitored groundwater level data to assess stress

The same level of assessment need not be applied across a study area. Rapid level assessments could suffice in low usage areas, in low stress areas or in instances where usage is expected to have limited impact. Assessments that are more detailed could be undertaken in areas where specific problems occur or in areas where the underlying groundwater system is clearly stressed. During the preparatory phase and prior to commissioning GRDM assessments, significant water resources in a study area requiring higher levels of assessment must be identified. These are referred to as multilevel GRDM assessments.

5.3 Recommended procedure

A desktop assessment should be the forerunner to all RDM assessments, including those where rivers, wetlands or estuaries are driving issues. Part of the desktop GRDM assessment should include consideration of the state of stress of the groundwater system based on indicators highlighted in section 4.2 and the Stress Index presented in Chapter 9.

In the absence of a recognised procedure for setting the level of confidence required for a GRDM assessment, the following approach should be adopted:

In instances where compulsory licensing is required (i.e. water use exceeds available long-term yield), comprehensive GRDM assessments are to be undertaken.

In instances where no indications of stressed groundwater systems are observed and the desktop GRDM assessment indicates that groundwater use is limited and potential use will have an insignificant or low impact, then a rapid GRDM assessment could be adequate.

In instances where a large area has to be assessed or the desktop GRDM assessment does not provide adequate information on which to base a decision, then a Scoping Study should be considered. From this, it must be decided whether a rapid, intermediate, comprehensive or multilevel assessment is required.

In instances where a low degree of stress is interpreted, moderate groundwater use is observed or low to moderate impacts or potential impacts are evident, then an intermediate GRDM assessment may be required. Impacts may include lowering of water tables or deteriorating groundwater quality on a local scale.

In instances where:

- the groundwater system is considered to be stressed,
- large volumes of groundwater are abstracted,
- the impact of an activity on the groundwater system is or could be considered to be high,
- incidences of groundwater-related disputes or conflicts are common,
- or highly sensitive and important groundwater-dependent ecosystems are prevalent within a significant water resource,

then a comprehensive GRDM assessment should be commissioned.

While it is strongly argued that all RDM assessments should include all components of the hydrological system (rivers, wetlands, groundwater and estuaries), not all components have to be assessed at the same level of confidence. However, for the IWRM vision of the NWA to be addressed, all components have to be considered.

5.4 In summary

Four levels of GRDM assessment are recognised – desktop, rapid, intermediate, comprehensive – with each providing an increased level of confidence. Increased levels of commitment and resources are required to attain higher levels of confidence. Desktop GRDM assessments can be completed in a matter of hours, but comprehensive GRDM assessments may take over a year to complete. The same level of assessment need not be applied across a study area, and a multilevel GRDM assessments approach can be adopted. Rapid level assessments could suffice in low usage areas, in low stress areas or in instances where usage is expected to have limited impact. Assessments that are more detailed may be undertaken in areas where specific problems occur or in areas where the underlying groundwater system is clearly stressed. Scoping studies can be undertaken prior to commissioning GRDM assessments to identify ‘significant’ water resources in a study area requiring higher levels of assessment.

6 UNDERSTANDING LINKAGES TO OTHER COMPONENTS OF RDM

It is important to understand the linkages of groundwater to other components of the water cycle since these links quite often provide the legal basis for groundwater protection in these instances. The two components that are specifically addressed in the NWA are BHNs and the role of groundwater to contribute to EWRs.

6.1 The role of groundwater in addressing basic human needs

The majority of the 22 million South Africans that have been provided with water since 1994 have been supplied from groundwater resources. The Reconstruction and Development Programme (RDP) instituted a programme of drilling, testing and equipping boreholes. Because groundwater is generally found near the point of need, boreholes drilled close to villages and rural settlements was used to establish basic water supplies. There are indications that 14 000 rural villages could be served from groundwater. In the Eastern Cape alone, the water supply to more than 80% of the 5 700 communities in the province could be groundwater-based.

A basic supply of water is one of only two rights to water enshrined in the NWA. Groundwater is now recognised as a strategic resource that can play a major role in the fight against poverty and in easing the burden of women in rural areas. The sustainable use of groundwater is paramount in attaining the goal of each South African having access to at least 25 ℓ/pppd of water.

6.2 Baseflow in rivers

One of the main components of the ecological Reserve is the protection of aquatic biota. It thus became imperative that the interaction between groundwater contribution to baseflow be quantified so that this component can be included in the ecological Reserve. Closer cooperation with ecologists also became necessary.

A river hydrograph consists of 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 the word “baseflow” is generally known to many hydrologists as delayed flow components (mainly groundwater), as opposed to a quick, direct runoff. Thus baseflow itself is not indicative of origins of water sources. The baseflow is normally separated by removing the direct runoff from a hydrograph. 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 baseflow in rivers. (Xu et al, 2002).

To understand possible contributions to baseflow from groundwater the possible relationships between river flow and groundwater must first be discussed. This is outlined below in Table 6.1.

Table 6.1 Interaction between surface water (SW) and groundwater (GW) flow (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 Exchange	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.

6.2.1 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:

6.2.1.1 Herold method

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

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

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 groundwater growth factor (%).

The equation shows that the current groundwater component Q_{gi} 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 DW&EA's gauge No X3H00l 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).

6.2.1.2 Smakhtin method

Smakhtin (2001) proposed a formula calculating surface runoff. Groundwater contribution is the total flow minus quick surface runoff.

$$Q_{si} = Q_{gi-1} \cdot filter + 0.5 \cdot (1 + filter) \cdot (Q_{Ti} - Q_{Ti-1})$$

where the filter is about a value varying from 0.95 to 0.99. However it has been noticed that the selection of the initial value of baseflow could 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.

6.2.1.3 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):

$$Q_g = Q_T \cdot \left(\left(C_r - C_d \right) / \left(C_g - C_d \right) \right)$$

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. (6.3) makes use of groundwater concentration C_g, direct runoff concentration C_d and stream concentration C_r.

It must be applied with care near the sea and in areas where the annual recharge is erratic and low.

6.3 Groundwater dependent ecosystems

The NWA recognises the need to set aside water for aquatic ecosystems. Groundwater can contribute to the health of aquatic ecosystems through discharges to surface water bodies. (Parsons, 2003). However, the NWRS also recognises the importance of terrestrial ecosystems that need protection.

Similarly, the hyporheic zone is contained within the land–water ecotone and is functionally a composite between surface and groundwater ecosystems. It provides a number of ecologically important services, including thermal, temporal and chemical buffering, habitat, flow augmentation and refugia. The zone may be significantly different from the overlying surface water body and the underlying aquifer system. Brown et al. (2003) noted that upwelling (or discharge) of groundwater creates patches of high productivity in the hyporheic zone and aquatic ecosystems, supporting greater faunal densities and diversities when compared to non-upwelling situations.

Case study: Doring River

Groundwater plays a crucial role in providing refugia during dry periods. In summer, fish survive in groundwater-fed pools when surface flows cease in the Doring River. It was recently observed that indigenous fish only use pools fed by a fresh groundwater source, while alien fish were found in all pools.

(Brown et al., 2003)

Groundwater dependent ecosystems represent a small, but diverse and important component of biological diversity. Their recognition as a distinct group is relatively recent and may largely be attributed to work by Hatton and Evans (1998).

The dependency of ecosystems on groundwater is based on one (or more) of four basic groundwater attributes:

- **flow or flux** - the rate and volume of supply of groundwater;
- **level** - for unconfined aquifers, the depth below surface of the water table;
- **pressure** - for confined aquifers, the potentiometric head of the aquifer and its expression in **groundwater discharge areas**;
- **quality** - the chemical quality of groundwater expressed in terms of pH, salinity and/or other potential constituents, including nutrients and contaminants. (Sinclair Knight Merz Pty Ltd, 2001)

The response of ecosystems to change in these attributes is variable. There may be a threshold response in some cases, whereby an ecosystem collapses completely if a certain attribute value is exceeded.

Hatton and Evans (1998) recognised five classes of ecosystem dependency on groundwater, as follows:

- *Ecosystems entirely dependent on groundwater (obligate systems)* - communities where only slight changes in key groundwater attributes below or above a threshold would result in their demise.

Examples include ecosystems with very narrow ecological ranges for water quality or groundwater level or pressure, those dependent entirely on surface or near surface discharge of groundwater for survival and aquatic ecosystems whose habitat is groundwater or entirely groundwater derived. An indicator plant in a South African context would be the ground orchids found in many wetlands.

- *Ecosystems highly dependent on groundwater* - communities where moderate changes in groundwater discharge or water tables would result in a substantial change in their distribution, composition and/or health. Such ecosystems utilise both groundwater and surface and/or soil water. They would be substantially modified if the supply of groundwater ceased.

- *Ecosystems with proportional dependence on groundwater* - such ecosystems do not exhibit the threshold-type responses of the more highly dependent ecosystems. Rather as the relevant groundwater attributes change, there is a proportional response in the ecosystem, particularly in terms of distribution. A large number of examples of this type of ecosystem were identified by Hatton and Evans (1998). Many of them are base flow and permanent lake ecosystems.

- *Ecosystems that make limited or opportunistic use of groundwater (facultative systems)* - groundwater appears only to play a significant role in the water balance of such ecosystems at the end of a dry season or during extreme drought. In the short term, communities may tolerate lack of access to suitable groundwater; however they will decline and ultimately collapse if this state is prolonged excessively.

There is a substantial body of literature on the ecology of groundwater dependent ecosystems but most was based on investigations undertaken from a purely ecological perspective. Few studies considered groundwater processes and specific details of ecosystem or community dependency on groundwater.

Hatton and Evans (1998) identified four types of groundwater dependent ecosystem:

- terrestrial vegetation;
- river base flow systems;
- aquifer and cave ecosystems;
- wetlands.

It has since become apparent that there are at least two additional distinct types of groundwater dependent ecosystem, namely:

- terrestrial fauna;
- estuarine and near-shore marine ecosystems.

(Sinclair Knight Merz Pty Ltd, 2001)

6.3.1 Terrestrial vegetation

This class of groundwater dependent ecosystem includes vegetation communities that do not rely on expressions of surface water for survival, but which have seasonal or episodic dependence on groundwater. Groundwater systems may be locally recharged during a pronounced wet season,

Terrestrial vegetation communities are influenced by several of the key groundwater attributes, as follows:

- *Level* - most terrestrial groundwater dependent ecosystems require groundwater levels in unconfined aquifers to be at least episodically or periodically within their root zone. Groundwater would typically be required to satisfy evaporative demand during times when soil water availability is low.

- *Flux* - in addition to being at a level accessible to plant roots, groundwater flux would need to be sufficient to sustain a level of uptake by vegetation that at least partly satisfied evaporative demand.

- *Quality* - salinity would typically be the key indicator of groundwater quality for such ecosystems. Terrestrial ecosystems may also be sensitive to groundwater contamination by nutrients, pesticides or heavy metals, however little is known of their response.

6.3.2 Wetlands

The link between groundwater and wetlands is still poorly understood (and researched) in South Africa. However, it is suspected that many wetlands depend at least to some degree (both spatially and temporally) on a contribution from groundwater. This is especially true during the dry season where the groundwater contribution is critical in sustaining the ecology of the wetland.

The link is mostly geologically controlled and to understand the interaction, a three dimensional model must be considered. The most basic types of interaction are illustrated in the following diagrams (Adapted from RAMSAR Conference, 2005):

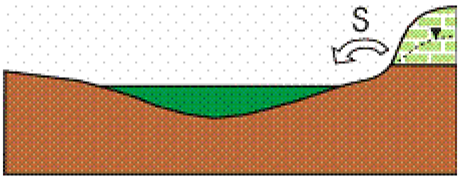


Figure 6.2 Water seeping from an aquifer onto the surface of a wetland

S: spring. Water seeping from an aquifer onto the surface of a wetland. Often this is associated with the location of an aquiclude beneath the aquifer.

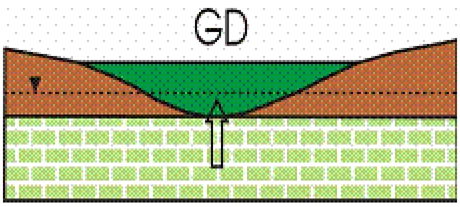


Figure 6.3 Water moving vertically upwards into a wetland

GD: groundwater discharge. Water moving vertically upwards into a wetland from an underlying aquifer. The piezometric head/water level of the aquifer is higher than the water level in the wetland. In some instances a lower permeability layer between the wetland and the aquifer that could limit water flow.

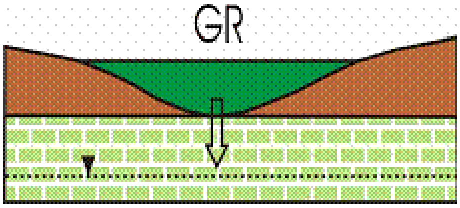


Figure 6.4 Water moving vertically downwards from a wetland

GR: groundwater recharge. Water moving vertically downwards from a wetland to an underlying aquifer. The piezometric head/water level of the aquifer is lower than the water level in the wetland. In some instances a lower permeability layer between the wetland and the aquifer limit water flow.

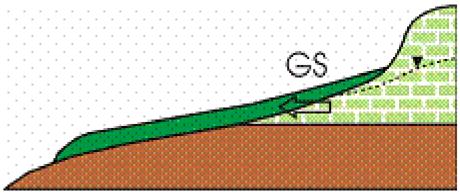


Figure 6.5 Water moving laterally into a wetland

GS: groundwater seepage. Water moving laterally into a wetland from an adjacent aquifer. In some instances a lower permeability layer between the wetland and the aquifer limit water flow.

It is seldom that only one type of interaction takes place. Figure 6.6 illustrates possible multi interactions within a hypothetical wetland:

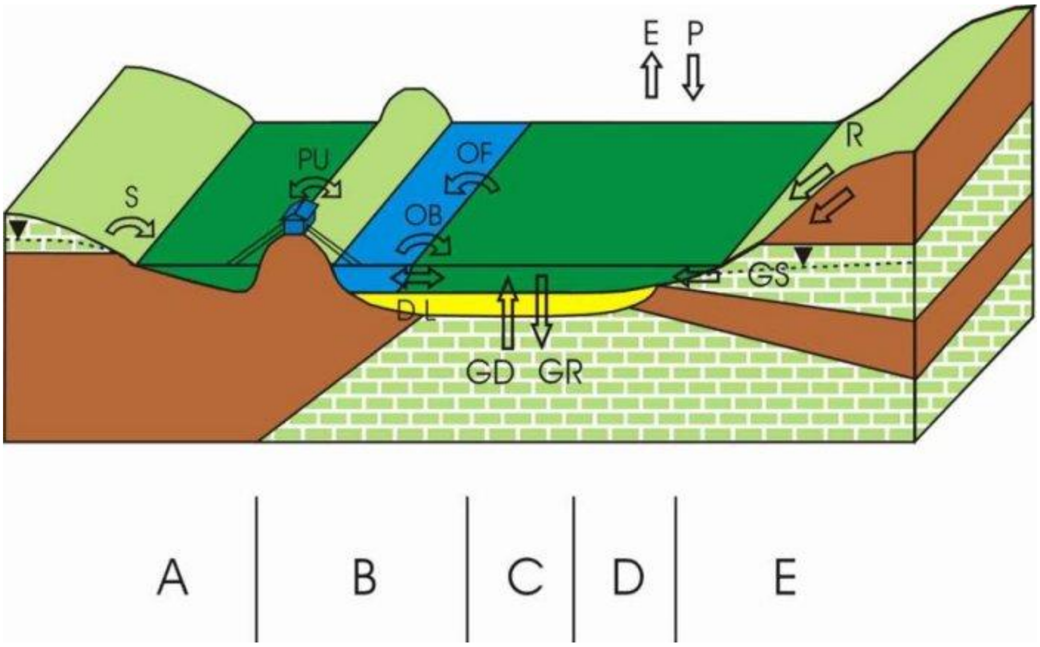


Figure 6.6 Possible multi interactions within a wetland

It shows a cross-section of a hypothetical wetland where different water transfer mechanisms dominate in different zones of the wetland.

- Hydrological inputs to Zone A are dominated by spring flow (S) and outputs by pumping (PU).
- In Zone B over-bank flow from the river (OB) dominates.
- Zone C is an area of exchange with groundwater (GD, GR).
- The hydrology of Zone D is dominated by precipitation (P) and evaporation (E).
- In Zone E inputs come from groundwater seepage (GS) and runoff from the adjacent slopes (R).

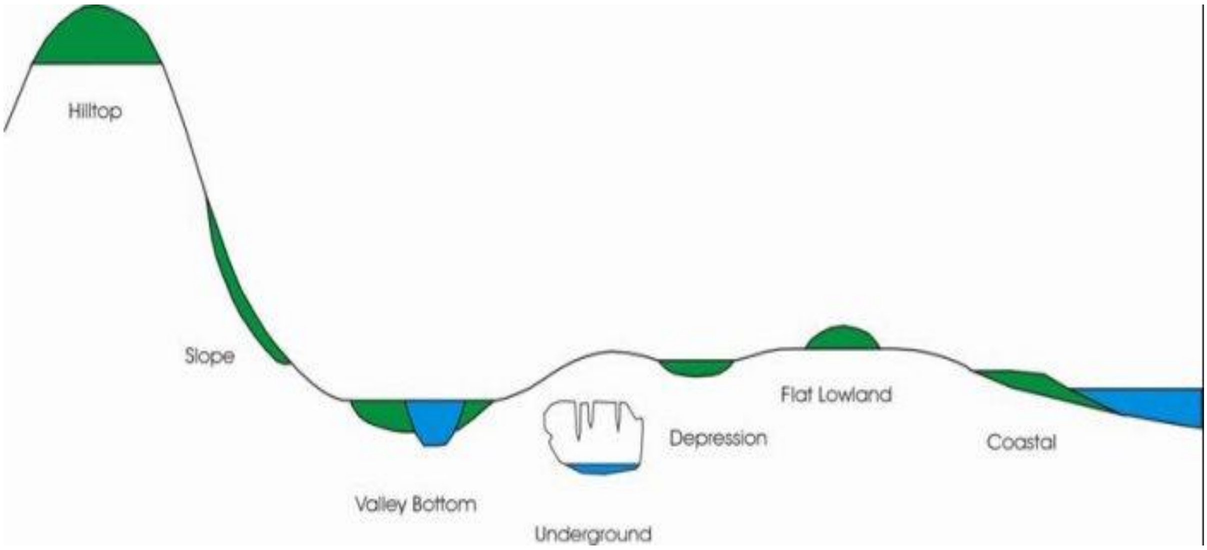
Cross-section diagrams will probably need to be produced for different periods (most notably for wet or dry seasons) since the water transfer mechanism may change; for example the interaction between the aquifer and wetland may alter discharge and recharge as water table levels change (RAMSAR Conference, 2005).

6.3.3 Linking landscape location and water transfer mechanisms

According to the RAMSAR Convention, seven types of wetland (irrespective of their groundwater dependency) are recognised based on landscape location and water transfer mechanisms. Their possible interaction with groundwater (where applicable) is indicated in table 6.2 and graphically displayed in Figure 6.7:

Table 6.2 Link between landscape and water transfer mechanisms for wetlands

Landscape location	Subtype based on water transfer mechanism
Flat upland wetlands	Upland surface water fed
Slope wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Valley bottom wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Underground wetlands	Groundwater-fed
Depression wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed
Flat lowland wetlands	Lowland surface water fed
Coastal wetlands	Surface water-fed
	Surface and groundwater-fed
	Groundwater-fed



6.3.4 Estuarine and near shore marine systems

Although recognised internationally, very little information is available on the interaction between estuaries and groundwater in South Africa.

A variety of groundwater dependent ecosystems are described in the literature. Several examples are listed below.

- *Coastal mangroves and salt marshes* - While seawater is considered to be the primary water source for most of these vegetation communities, sites have been noted where mangroves occupy discharge areas consisting of relatively fresh groundwater (Adam 1994). The extent of groundwater dependency is unknown.

- *Coastal lakes* – The coastal lakes in KwaZuluNatal such as St Lucia and Kosibay depend on groundwater during the dry season.

- *Sea grass beds* - the distribution of sea grass beds in some coastal areas is influenced by groundwater discharge in Australia (PPK 1999).

- *Marine animals* - some marine and estuarine animals depend on groundwater discharge to provide a suitable habitat or an appropriate environment in which species of plant and/or animal they eat will prosper. Groundwater discharge may be in the form of direct off –shore discharge or base flow into streams that discharge to the ocean. Examples of groundwater dependent fauna include crocodiles, turtles, fish and macro -invertebrates (Hatton and Evans 1998; PPK 1999; Sinclair Knight Merz 2000). Groundwater flux will strongly influence dependency of coastal and estuarine ecosystems. Direct discharge fluxes and/or base flow volumes would need to occur at a sufficient rate that groundwater significantly dilutes seawater.

6.3.5 River base flow systems

This category of ecosystem was devised by Hatton and Evans (1998) to include the many ecosystems that are dependent on groundwater derived base flow in streams and rivers. Dry season flows in permanent and semi-permanent streams in northern Australia may be almost entirely provided by base flow. Base flow also contributes to wet season flows in such streams, but not to the same extent (Cook *et al.* 1998). Base flow may contribute year round to flows in coastal streams in south -eastern Australia and may contribute to flow in inland streams, although the extent of the contribution may be difficult to determine in some cases due to river regulation (Hatton and Evans 1998). Riparian and aquatic ecosystems in base flow dependent streams would be, to a greater or lesser extent, groundwater dependent themselves. Demarcation between groundwater dependent terrestrial vegetation, wetlands and base flow systems may be difficult, with the three types of community representing ranges on a spectrum of habitat, groundwater and surface water dependency.

6.3.6 Cave and aquifer ecosystems

This category comprises the aquatic ecosystems that may be found in free water within cave systems and within aquifers themselves. Gilbert (1996) argued that aquifer ecosystems represented the most extended array of freshwater ecosystems across the entire planet. Aquifers themselves support diverse array of ecosystems. Their fauna largely consists of invertebrates. Some ecosystems (e.g. in riverine plains) exist along a continuum between fully aquatic communities and fully aquifer communities (Danielopol 1989). Aquifer ecosystems are not necessarily confined to near surface environments. The so -called stygofauna (animals occupying cave or aquifer habitats) have been identified at depths of up to 600 m (Longley 1992). The environment in which aquifer ecosystems develop is characterised by darkness, consistency and persistence of habitat and low energy and oxygen availability. Their stable and confined environment results in high levels of endemism and high proportions of relictual species compared with surface environments (Danielopol 1989). Groundwater level, flux and quality are the three attributes likely to be of greatest significance to aquifer ecosystems. Where the composition of aquifer ecosystems change with depth, reductions in groundwater level it may result in the loss of particular species or communities. Any change in groundwater level might also result in marked change in groundwater quality.

Ecosystems in these aquifers are highly specialised and may be lost entirely with changes in groundwater level of only 1 -2 m (Humphreys 1999). Subtle changes in groundwater quality due to contamination by (e.g.) agricultural chemicals or septic tank effluent may result in changes in ecosystem function. The potential sensitivity of aquifer ecosystems to changes in groundwater quality raises the prospect of their use as bio -indicators (Gilbert 1996).

6.4 Terrestrial fauna

Descriptions of groundwater dependent ecosystems in the previous sections have mainly concentrated on plant communities. These communities provide habitat for a variety of terrestrial, aquatic and marine animals, which by extension must also be groundwater dependent. However there is an additional group of groundwater dependent fauna whose reliance on groundwater is not based on the provision of habitat, but as a source of drinking water. Groundwater, as river base flow or discharge into a spring or pool, is an important source of water across much of the country and other areas with semi -arid climate. Its significance is greater for larger mammals and birds, as many smaller animals can obtain most of their water requirements from respiration. Provision of water has allowed larger populations of wildlife to be sustained than would otherwise be the case. Groundwater dependent terrestrial and riparian vegetation and wetlands may be used by terrestrial fauna as drought refuges. Access to groundwater allows the vegetation to maintain its condition and normal phenology (e.g. nectar production, new foliage initiation, seeding). Populations of some birds and mammals retreat to these areas during drought and then recolonise drier parts of the landscape following recovery. The long term survival of such animal populations relies on maintaining the vegetation communities and ensuring their water requirements are met. The key groundwater attributes will be flux, level or pressure, depending on the hydrology of the system providing the water.

7 Detailed description of Methodology

7. 1 Project Background and Objectives

The purpose of this phase is to:
Initiate a GRDM study
Set out the objectives
Set the level of confidence of the GRDM assessment

7.1.1 Responsibility

A GRDM study can be initiated by DW&EA Head Office as part of the compulsory licensing process, or by a Regional Office in response to a licence application or an anticipated license application. This is largely a DW&EA management task undertaken by the RDM Directorate and the assigned RDM Study Manager, with specialist groundwater input being provided by DW&EA personnel. When initiating a study:

- Define the study area.
- Set the level of confidence of the GRDM assessment
- Set the project Terms of Reference
- Identify and appoint the multidisciplinary assessment team

The basic unit of any GRDM assessment is the **quaternary catchment**, but the area undergoing compulsory licensing, or the scale or extent of the proposed application, can also define the extent of the study area.

A private individual/company may also initiate such a study as long as it is realised that it remains a legal process that requires the signature of the Minister of W&EA (or delegated authority).

7.1.2 Approach

As a means of initiating the study and setting the level of confidence required (and hence the Terms of Reference), a desktop GRDM assessment should be undertaken. This is done using the GRDM Assessment Software included with this manual. This assessment will provide an indication of recharge, basic human needs, EWR and the groundwater allocation. If information is available regarding the volume of groundwater abstracted, then the Stress Index of a catchment can be determined (see section 7.4.2). The geohydrologist undertaking the assessment needs to be both experienced and familiar with the area of interest.

In some cases, a Scoping Study can be undertaken if more detailed information is required before the level of confidence can be set. The Scoping Study would aim to provide information about:

- the geographical extent of the study area and a brief description thereof;
- the role of groundwater in terms of sustaining other components of the hydrological system (baseflow to rivers, wetlands and estuaries);
- the degree of groundwater dependence (both social and environmental), including volumes of groundwater abstracted;
- aquifer stress (quantity and quality);
- geohydrological data and information available.

A key outcome of the Scoping Study is a recommendation regarding the level of GRDM assessment required for the study area. This is also an ideal time to interact with other specialists regarding groundwater interaction with other components so that these requirements can be built into the Terms of Reference.

A factor controlling the success of any project is the completeness and clarity of the Terms of Reference. Investment of both time and effort into the Terms of Reference is hence crucial. The Terms of Reference are to state clearly:

- the extent of the study area,
- the level of GRDM assessment required,
- the key tasks to be completed,
- the key outcomes from the GRDM assessment,
- any specific methods or approaches that need to be followed and
- the schedule of the project.

7.1.3 Key outcomes

The four key outcomes of the Project Background and Objectives are described as follows:

Definition of study area – a map is to be produced at a suitable scale outlining the extent of the proposed GRDM assessment.

Level of GRDM assessment – the level at which the GRDM assessment is to be undertaken is defined (rapid, intermediate, comprehensive).

Project Terms of Reference – Terms of Reference are to be compiled that clearly state the nature and extent of the GRDM assessment required.

Appointment of study team – if the project team is to comprise members outside of DW&EA, organisations capable of undertaking the assessment need to be identified and invited to tender for the work.

7.2 ASSESSMENT OF THE STUDY AREA

The purpose of this phase is to:

Collect existing geohydrological and related data for the study area with emphasis on Resource Integrity

Collect additional geohydrological data through appropriate geohydrological investigation

Describe the study area in terms of its physical and geohydrological characteristics in detail appropriate to the level of GRDM assessment required

Develop a conceptual understanding of geohydrological conditions in the study area and linkages to other components of RDM

7.2.1 Preamble

The GRDM assessment process may not be linear, and the development of a sound conceptual understanding of geohydrological conditions is required before classifying a resource, determining the Reserve and setting RQOs. As a result, the second phase of the GRDM process entails data gathering and analysis typical of any groundwater resource assessment, but ensuring that the information is adequate to classify a resource, determine the Reserve and set RQOs in the manner prescribed in this manual and at the level specified in the project Terms of Reference. Emphasis should be placed on resource Integrity to ensure its incorporation into either the Classification of the Resource or the Reserve.

7.2.2 Data sources

A wide range of data and information can be used to characterise the geohydrology of an area. At desktop and rapid levels of assessment, national scale data sets may be the only sources of reliable information. These would be supported by anecdotal information and the local knowledge and experience of the team undertaking the assessment. For intermediate and comprehensive GRDM assessments, site-specific data have to be collected. Based on the amount and quality of data available, the geohydrologist will need to provide an indication of the level of confidence of the assessment. Possible sources of data are listed in Table 7.1.

Table 7.1: Possible sources of data used during GRDM assessments

Data Needed	**Data and Information**	**Source**
Study area	Quaternary catchment boundaries	WR90
Population data	Population statistics	Central Statistical Services
Conservation areas		DW&EA
Water sources	Flow gauging stations	DW&EA
Physiography	Topographical maps - 1:250 000 - 1:50 000 (if needed)	Dir. Surveys and Land Information
Climatic data	Rainfall data Evaporation data	Weather Bureau WR90 SA Atlas of Agrohydrology and Climatology
Geology	Geological maps - 1:250 000 - 1:50 000 (if available)	Council for Geoscience
Geology Physiography	Remote sensing maps and data - satellite images - aerial photographs	Satellite Applications Centre Dir. Surveys and Land Information
Soils	Soil maps	Department of Agriculture Agricultural Research Council WR90
Drainage	Flow data Wetland inventory	DW&EA WR90
Vegetation		SANBI WR90
Geohydrology	Geohydrological maps - national groundwater maps - harvest potential map - groundwater vulnerability map - 1:500 000 geohydrological maps	WRC DW&EA
Geohydrological data	Geohydrological data - national groundwater database - hydrochemical database - geohydrological reports	DW&EA: NGDB DW&EA Regional Offices Water Research Commission Local authorities Consultants GRIP (where applicable)

A very valuable source of data is a hydrocensus, although this is normally only warranted for studies at an intermediate or comprehensive level. This entails visiting landowners in an area and collecting as much geohydrological information as possible from them. This includes information pertaining to geology, drilling depths, borehole yields, groundwater levels, groundwater usage and other site-specific issues of relevance. During the visit, parameters such as depth to groundwater and quality (EC) may be measured, and water samples collected. This information, together with that from the literature and database surveys, can be used to compile a geohydrological model of the study area and be the basis for planning further fieldwork. Further geohydrological investigative work could include remote sensing, geophysical surveys, drilling and testing and chemical and isotope analyses. In the case of comprehensive GRDM assessments, numeric modelling may be warranted.

7.2.3 Report structure

It is difficult to provide a template of the information required, as the detail of information will vary according to the level of GRDM assessment undertaken, the nature and extent of data available for the area and the particular area being assessed. However, the type of information required to build a sound geohydrological conceptual understanding of an area is presented in Table 7.2. This list could also be used as a basic template for the geohydrological report to be prepared on completion of the study.

Table 7.2: Basic information required for a geohydrological description of a study area

1. Introduction

Terms of Reference
Project team
Sources of data
Work undertaken

2. Background Information

Locality and extent of study area (map), including quaternary catchments and catchment areas
Population and sources of water
Land use (map), including urban, agricultural, forestry, mining, industry
Conservation and protected areas (map)
Water sources, including dams, interbasin transfer schemes, groundwater etc.

3. Physiography and Climate

Topography (map), including slope, geomorphological classification and mountain ranges
Climate, including rainfall (volumes, seasonality) and evaporation (volumes, seasonality) (map)
Geology (map), including lithology, stratigraphy and structure
Soils
Drainage, including rivers, dams and lakes, wetlands, springs and vleis, mean annual runoff (MAR), baseflow and baseflow indices, groundwater contribution to baseflow and ecological water requirements (EWR) (if available)
Vegetation (map), including types and classification (e.g. Acocks, Low and Rebelo),

4. Geohydrology

Aquifer types (primary, secondary) (map)
Hydraulic characteristics and range of parameters (T, K, S)
Typical drilling targets
Boreholes and borehole characteristics (depth, yield, construction) (map)
Groundwater abstraction and use (domestic, RDP, industrial, agricultural, mining)
Groundwater levels and depth to groundwater, groundwater level contour map and hydraulic gradient (map), typical seasonal and annual fluctuations of groundwater levels– particularly in the vicinity of surface water bodies
Possible factors that impact on resource Intergrity
Groundwater quality (e.g. Piper or Durov diagrams, contour maps, statistical analyses and description)
Source and potential sources of groundwater contamination
Known incidences of groundwater contamination in a catchment
Recharge
Groundwater potential, including harvest potential
Surface– groundwater interaction, including groundwater contribution to baseflow, groundwater-dependent ecosystems and wetlands
Aquifer classification (sole source, major, minor, poor) (map)
Aquifer vulnerability (map)
Aquifer stress status (see Section 9.2.3)
Conceptual geohydrological model of study area, including a water balance

7.2.4 Key outcomes

The key outcome of this phase of the assessment is a draft report describing the study area in general, and the geohydrological conditions and conceptual model in particular. The report is to include as much of the information listed in Table 7.2 as possible, including tables and maps. Information used to prepare the report will then form the basis on which delineation of units, Classification, Reserve determination and the Resource Quality Objectives are based.

7. 3 DELINEATION OF RESOURCE UNITS

The purpose of this phase is to:

Demarcate and describe significant water resources in the study area

7.3.1 Preamble

The key outcome of this step is a map demarcating groundwater resource units, each of which is to be classified, a Reserve assessment undertaken and RQOs set. Other components of the water cycle such as EWRs must be considered during the delineation process to assess possible interdependency and promote the integrated water resource management vision of the NWA. It must be borne in mind that each delineated unit will have to classified and eventually linked to other components of the water cycle.

7.3.2 Delineation of resource units

A three-tier system of delineation is used. Primary delineation is based on the default use of **quaternary catchment** boundaries and is usually only used for desktop and rapid assessments. More complicated and data-intensive delineation is undertaken for intermediate and comprehensive GRDM assessments, including a detailed delineation of stressed areas where the water use is considered to be unsustainable. It must always be borne in mind that whatever the most appropriate delineation, it must be translated back into a management unit that the CMA can manage.

7.3.2.1 Primary delineation

By definition, **quaternary catchments** are used as the primary delineation of water resource units in RDM assessments. In the case of desktop or rapid assessments, insufficient information will be available for refining resource units further, and most assessments will therefore be based on quaternary catchments.

7.3.2.2 Secondary delineation

Secondary delineation should largely be dictated by the interaction of groundwater with other ecological components. Dollar et al (2007) brought in the concept of nodes where it is understood that this refers to an area where there is interaction with other components or where the groundwater resource itself might behave differently than in the regional sense. This is referred to as an Integrated Unit of Analysis (IUAs).

The groundwater nodes need to be established with the objective of predicting probable EWRs that may be partially or totally dependant on groundwater. The EWR nodes may capture the following:

- lithological boundaries at aquifers and aquitards;
- groundwater contribution to base flow;
- groundwater contribution to wetlands and other groundwater dependent ecosystems;
- geological faults;
- groundwater levels, and
- springs.

It is recommended that a six-tier procedure be followed to determine groundwater dependent EWR areas of interaction that may include:

- groundwater fed base flow;
- groundwater levels;
- springs;
- geological faulting, and
- .geological contacts

Because of the number of factors to be considered, setting resource unit boundaries will probably be an iterative process requiring modification until all component requirements have been accommodated.

The second level of delineation could also be based on aquifer type (i.e. primary , secondary or dolomitic aquifer) if required. Though these aquifers may be linked, the nature of subsurface flow in them is so different that they warrant obvious delineation. In some cases, it may be desirable to regroup these aquifer types into a single groundwater unit. This is considered and motivated during the third level of delineation.

An example: Crocodile River (West)

In the case of the Crocodile River (West), it was found that groundwater discharge from the dolomitic aquifer system accounted for about 60% of baseflow (DW&EA, 1999). Because of the unique role groundwater played in the hydrological system, the dolomitic aquifers needed to be delineated as a distinct water resource unit.

7.3.2.3 Tertiary delineation

This would normally only be required when certain portions of the resource is already stressed and would therefore require very detailed regional information that would assist in setting fairly local RQOs. Provision was made for this in the GRDM software.

7.3.3 Delineation criteria

Two criteria are recognised that could be used as the basis for delineation, namely physical or management criteria. The criterion could be used singularly, or in conjunction with other criteria. It is necessary to specify which criteria or characteristics were used in the delineation process, and motivate why that particular characteristic was considered the most appropriate.

7.3.3.1 Physical criteria

Typically, delineation based on physical criteria would consider one or more of the following:

- Geology

- Climate
- Topography and geomorphology
- Recharge
- Groundwater levels and flow directions
- Temporal hydrostatic response patterns
- Groundwater quality
- Groundwater use (and stress)
- Groundwater-dependent ecosystems.

7.3.3.2 Management criteria

The outcome of a GRDM assessment and aquifer management goals reflect key components of the NWRS. In some cases, it may be difficult to manage an aquifer on the basis of physical delineation considerations and it may be more practical and meaningful to use management criteria for delineation. Examples could include property, water user association, catchment management, water management and political boundaries.

7.3.5 Key outcomes

The key outcome of this phase of the GRDM assessment is a map demarcating significant groundwater resource units with nodes, each of which is to be classified, a Reserve assessment undertaken and RQOs set. This map will also help ensure that the RDM team has a common understanding of the study area.

7.4 RESOURCE CLASSIFICATION

The purpose of this phase is to:

Determine the current classification of each groundwater resource unit

Define the present class of each resource unit in terms of minimally used, moderately used and heavily used

7.4.1 Preamble

The concept of classification has changed significantly over the last 10 years, since the NWA was promulgated. The first methodologies developed for GRDM assessments were incorporated into the RDM manuals (DWAF, 1999). The work of Xu *et al*. (2003) and Colvin (2003) on GRDM methodologies superseded this. These attempts were all considered as “preliminary” approaches to GRDM methodologies in a legal sense, because there was no classification system in place at the time.

In all previous approaches, the Resource was assessed against a “pristine state” and the current and future state of the Resource was measured against this. In the Classification process proposed by Dollar et al (2006), Step 4 requires the setting of a baseline configuration for the Resource that would be used as a future reference point. Both these concepts do not have great relevance in groundwater. The main objective of the Classification process is to ensure that the Resource can be utilised sustainably in the long term if the proposed class is adhered to and none of these concepts contribute to its realisation. This has led to the concept of groundwater stress as an indicator that could replace the baseline configuration. Stress should be defined in such a way that it reflects the long term sustainable utilisation of the Resource incorporating all the legal requirements that must be considered.

7.4.2 The Classification process

The Classification process that was proposed by Dollar et al (2006) forms the basis for this assessment to ensure smooth integration with other components.

Instead of assuming that the Quaternary Catchment is the default unit, Dollar *et al.(2006)* introduced the term ”Integrated Unit of Analysis”(IUA). In most instances, this unit will be the Quaternary Catchment, but it allows for flexibility when a study is initiated.

While the principles on which the WRCS are based are sound and generic, the WRCS only addresses groundwater from an ecological and basic human needs perspective, which implies that the majority of aquifers in the country would, once again, receive no legal protection to ensure long-term sustainable utilisation. It also does not reflect the fact that groundwater, unlike surface water, is potentially available throughout the catchment, and is not limited to specific channels. This concept is important, since it would require a differentiated approach to groundwater within a catchment to ensure that the stressed areas are accommodated without impinging excessively stringent measures on the rest of the catchment. With this view in mind, a resource should be approached from a Resource Integrity angle where the factors that could impinge on the Ecological, System or Discharge Integrity can be assessed and incorporated in either the Classification or the Reserve.

Classification is the only legal mechanism that can be used to protect groundwater resources in the absence of an ecological link. The intention of the NWA is that the Reserve process should cover the detail of resource protection, and that protection measures be quantified in setting the RQOs. Since this linear route only addresses ecological requirements, a very large percentage of aquifers are excluded in the process. While it is true that there is always a BHN Reserve, the numbers attached are not significant in terms of resource protection. Groundwater that supplies small towns and communities falls into this category and they are in dire need of protection. The only legal framework through which this can be done is Classification. In the absence of an EWR component, Classification should be mapped directly to RQOs to provide the necessary protection.

Since water resources must be managed as a unit, groundwater cannot be treated as a separate entity within a catchment. When there is an ecological component involved, this can be accommodated through the proposed Classification System of Dollar *et al.* (2006) and then rolled on to the Reserve. When this is not the case, a classification system should be developed for groundwater that is compatible with the WRCS, but that makes provision for groundwater resource protection in the absence of an ecological component. This is done through the concept of System Integrity which will be discussed in more detail under RQOs.

The generic principles will be adhered to as far as possible and has been adapted as follows:

Table 7.1 Proposed Groundwater Resource Classification Process

Step 1	Delineate the units of analysis and describe the catchment status quo.
Step 2	Link value and condition
Step 3	Quantify groundwater contribution to Ecological Water Requirements (EWRs).
Step 4	Set Sustainability Base Configuration (SBC) scenario in the form of a Stress Index

Step 5	Evaluate scenarios within the IWRM process
Step 6	Evaluate sustainability scenarios with stakeholders
Step 7	Gazette class configuration

Step 1: Delineate units of analysis and describe the status quo

In most instances, it is assumed that the IUAs is the quaternary catchment, unless there are compelling reasons not to use it, such as when compulsory licensing is considered.

The detailed process is as follows:

- Determine the groundwater use in the catchment including human use;
- Identify a network of significant water resources and identify possible links to groundwater;
- Identify a network of nodes that link groundwater and surface water;
- Delineate IUAs based on above.

The groundwater nodes need to be established with the objective of predicting probable surface water/groundwater areas of interaction, specifically, of groundwater supplying water to rivers, springs, wetlands and other terrestrial ecosystems. To this end, a multi-tiered approach to establishing the location and number of nodes in a target catchment is recommended. The nodes may capture the following:

- lithological boundaries at aquifers and aquitards;
- groundwater contribution to base flow;
- groundwater contribution to wetlands;
- geological faults;
- groundwater levels; and
- springs.

Step 2: Link value and condition

The objective in *describing and valuing the use of water* is to determine the way in which water is currently being used in each socio-economic zone and to estimate the value generated by that use. This will provide the baseline against which the socio-economic implications of different catchment configuration scenarios can be assessed.

The description of water use will require for each user sector for each socio-economic zone:

- the allocated volume, and
- the level of assurance.

The objective in *describing and valuing the use of groundwater dependant ecosystems* is to determine the way in which groundwater dependant ecosystems are currently being used in each socio-economic zone, and to estimate the value generated by that use. This will provide the baseline against which the socio-economic and ecological implications of different catchment configuration scenarios can be compared. It is important to point out that while EGSAs should be identified and described (at least in qualitative terms), a baseline value can often only be described for some of these, as the information required is often not available without investing in a costly survey. It is also easier to measure changes in EGSAs values relative to a reference point than computing a baseline value.

Detail spelt out in this process will normally only be required at a very high level of assessment confidence such as when a compulsory licensing process is envisaged.

Step 3: Assess Ecological and Discharge Integrity.

Groundwater contribution to Baseflow in rivers

One needs to quantify the groundwater contribution to the EWR in rivers. This could either be diffuse or point sources. The following is a summary of the techniques:

- Baseflow maps
- Herold method of baseflow separation
- Darcy's Law
- Low maintenance flows

► Numerical groundwater flow models

Groundwater contribution to wetlands and GDEs.

The groundwater contribution to the flow towards wetlands and GDEs might be difficult to quantify, but they must nonetheless be identified to ensure that practical measures can be built into RQOs. Possible linkages are discussed in detail in Chapter 6.

Indicators would be a reduction in spring flow and wetlands that are dry during crucial periods.

Step 4: Assess System Integrity and set Sustainability Base Configuration (SBC) in the form of a Stress Index:

The concept of a baseline configuration in groundwater is not easy to quantify. However, the objective of Step 4 of the classification procedure is to set the sustainability base configuration in terms long term sustainable use. This is done in the form of a Stress Index as discussed in detail later in this section. The impact of abstraction must also be assessed in terms of the following so that System Integrity can also be assessed:

- Land stability – especially in dolomitic terrain
- Seawater intrusion due to over abstraction
- Local high volume abstraction
- Anthropogenic contamination

Limits of sustainability

Defining the point at which a resource is no longer being used in a sustainable manner is generally very difficult. The level of sustainability probably fluctuates through time, and impacts from over-use could manifest themselves some time after the impact was caused. The change from sustainable use to over-use is gradational, and not necessarily marked by some distinct change.

Indicators of quantitive unsustainable groundwater use include:

- reduction in spring or river flow
- vegetation die-off or reduced biodiversity
- land subsidence or sinkhole formation

- saline intrusion
- long term declining water levels on a regional level
- long term declining water quality levels not related to saline intrusion

For these to be good indicators, a **causative relationship** between groundwater abstraction and observed impact has to be established. While the work of Scott and Le Maitre (1997), Hatton and Evans (1998), SKM (2001) and Colvin et al. (2003) have been useful in helping to understand groundwater dependence, further work is required to provide practitioners with useful tools for establishing and assessing that dependence. A guide for assessing the status of groundwater units based on observed impacts resulting from groundwater abstraction is presented in Table 7.2.

Table 7.2: Guide for setting the present Class of a groundwater unit based on observed environmental impact indicators

CURRENT CLASSIFICATION	GENERIC DESCRIPTION	AFFECTED ENVIRONMENT
Minimally used (I)	The water resource is minimally altered from its pre-development condition.	No sign of significant impacts observed
Moderately used (II)	Localised low level impacts, but no negative effects apparent	Temporal, but not long-term significant impact to: -spring flow - river flow - vegetation - land subsidence - sinkhole formation - groundwater quality
Heavily used (III)	The water resource t is significantly altered from its pre-development condition.	Moderate to heavy impacts to: - spring flow - river flow - vegetation - land subsidence - sinkhole formation - groundwater quality

Defining stress

The concept of stressed water resources is addressed by the NWA, but is not defined. Part 8 of the Act gives some guidance by providing the following qualitative examples of 'water stress':

- Where demands for water are approaching or exceed the available supply;
- Where water quality problems are imminent or already exist; or
- Where water resource quality is under threat.

A groundwater stress index should reflect water availability versus water used and reserved. Currently recharge is related to water availability. Although this is strictly not always true, Principles 5 and 11 of the NWRCS were taken into account in this decision. As more reliable national datasets become available that would reflect water availability more accurately, recharge will remain the parameter to be used. Groundwater use should include water utilised by current water users, water required to sustain the Reserve as well as for BHN.

The Stress Index is defined as follows:

$$SI(\%) = \frac{gwUse + BHN + gwEWR}{Recharge} \times 100$$

Where

$gwUse$:	Current groundwater use in the IUA
BHN:	Current Basic Human needs in the IUA
$gwEWR$:	Groundwater contribution to the EWR in the IUA
$Recharge$:	Recharge (as a volume) in the IUA.

EWRs in this instance must be considered the groundwater contribution to sustain baseflow in rivers, to sustain the contribution to wetlands as well as other groundwater dependant ecosystems, including springs.

In calculating the Stress Index, the variability of annual recharge is taken into account in the sense that not more than 65% of average annual recharge can be allocated on a catchment scale (Table 7.3).

Table 7.3: Guide for determining the level of stress of a groundwater unit.

CLASS	DESCRIPTION	STRESS INDEX (%)
I	Minimally used	≤20
II	Moderately used	20–40
III	Heavily used	40–65

General Classification

Tables 7.2 and 7.3 form the basis of the classification process. However, in many cases it is quite obvious when a resource is being over-used or is stressed.

It is accepted that not all impacts can be covered in the above guiding tables. To accommodate other considerations, the generic descriptions used in Table 7.4 can be used to guide current classification in terms of System Integrity. Table 7.5 gives more guidance on possible abstraction impacts that can be difficult to quantify, but must nonetheless be evaluated.

This table should be used if it is not possible to calculate a Stress index.

Table 7.4: Present classification assessment based on System Integrity

PRESENT CLASSIFICATION	DESCRIPTION	GUIDE
I	Low abstraction volumes, no risk of subsidence, more than 1km from coastline, regional water	System Integrity largely unimpacted

	table stable.	
II	Moderate levels of abstraction with no long term impact on regional water level, small risk of subsidence, less than 1km from coastline.	Some localised impacts, but regionally stable
III	Moderate levels of abstraction with varying long term impact on regional water level, medium risk of subsidence, less than 500m from coastline.	Widespread impact

Table 7.5: Present classification assessment based on groundwater use

PRESENT CLASSIFICATION	DESCRIPTION	GUIDE
I Minimally used	Low volume groundwater usage, largely natural conditions, no negative impacts apparent	Stock watering, farm domestic water supply, rural water supply (Use ranges between 5% and 20% of recharge)
II Moderately used	Moderate volumes of groundwater usage, little or no negative impacts apparent	Small-scale irrigation, rural water supply, water supply for villages and small towns. (Use ranges between 20% and 40% of recharge)
III	High volumes of groundwater	Water supply for large rural

Heavily used	usage, but with little apparent long term negative impact	communities, medium to large towns, large-scale irrigation. (Use ranges between 40% and 65% of recharge)

Contamination is part of the System Integrity assessment and Table 7.6 could be helpful to guide the evaluation process.

Table 7.6 Present classification assessment based on observed groundwater contamination

PRESENT CLASSIFICATION	DESCRIPTION	GUIDE
I	Localised, low levels of contamination, but no negative impacts apparent	Largely unimpacted groundwater quality conditions prevail
II	Moderate levels of localised contamination, but little or no negative impacts apparent	Some localised contamination detected; may impact the purpose for which groundwater is used
III	Moderate levels of widespread contamination, which limit the use or potential use of the aquifer	Groundwater contamination is quite widespread but levels are relatively low; may impact the purpose for which groundwater is used

In assessing groundwater quality, the ambient groundwater quality of the Resource in question must always be considered. The basic assumption is that it should not differ significantly from natural and should retain its inherent “fitness for use” attributes. A table relating expected impact to land use was developed (Table 7.7).

A site-specific assessment using DRASTIC (Aller et al., 1985) can also be carried out, otherwise vulnerability as presented by Parsons and Conrad (1998) can be used (Table 7.8).

Table 7.7 Expected impact based on potential or expected groundwater contamination (adapted from Parsons and Wentzel, 2007)

EXPECTED IMPACT	LAND USE
Minimal impact	natural veld industrial area – (not chemical) pastures abattoirs irrigation – limited chemicals kraals rural area – low density
Moderate impact	sewage works – small (less than 1 Mℓ/d) spills – hazardous waste site – small industrial area – food processing irrigation – chemicals rural area – high density feedlots sewage works – medium waste site – medium (between 1 and 20 Mℓ/d)
Heavy impact	industrial area – chemical mine dumps urban area waste site – large hazardous waste sewage works – large (greater than 20 Mℓ/d)

	underground storage tanks industrial area – metal processing power generation waste site – hazardous

Table 7.8 Expected land use impact based on vulnerability

	VULNERABILITY (adapted from Parsons and Conrad, 1998)			
EXPECTED LAND USE IMPACT		Low	Medium	High
	Minimal Impact	I	I	I
	Moderate Impact	I	II	III
	Heavy Impact	II	III	Not allowed

Step 5: Scenario development within the IWRM process

The objective of Step 5 of the classification procedure is to evaluate scenarios within IWRM process so that a subset of catchment configuration scenarios can be put forward for stakeholder evaluation in Step 6.

The current Classification of the Resource should be used at this stage to present the *status quo* to the stakeholders and inform them of the implications thereof. It is for them to decide, taking the social and economic considerations into account, whether they would like to change the current Class to another Management Class. It is beyond the scope of this treatise to address the issues involved in that process.

Step 5 should therefore include:

a. Determine the current Classification as set out above.

b. Assess water quality implications (fitness for use) for relevant users.

c. Report on ecological conditions that might depend on groundwater.

Step 6: Evaluate scenarios with stakeholders

This phase will normally be part of the bigger assessment where groundwater has been integrated into the other components. The procedure as spelt out by Dollar et al (2006) should be followed.

It is crucial that if the MC is altered from the current Class that the risk associated with this be spelt out to the water users.

Step 7: Gazette class configuration

The same procedure as above applies.

7.5 QUANTIFICATION OF THE RESERVE

> The purpose of this phase is to:
>
> Quantify the groundwater component of the Reserve for each IUAs

7.5.1 Groundwater component of the Reserve

The groundwater component of the Reserve is the part of the groundwater resource that sustains basic human needs and in some instances contributes to EWR. Because groundwater is far more widespread geographically than surface water resources, that component of the geohydrological system which sustains the Reserve is only a part of the greater system considered under GRDM. To be able to quantify the groundwater component of the Reserve, we need to be able to estimate the volume of groundwater needed to BHN and groundwater contributing to EWR.

7.5.2 Quantification process

The Reserve addresses BHN and the Ecological Integrity of the Resource in question and must consider the following:

- Groundwater contribution to baseflow in rivers
- Groundwater contribution to wetlands
- Groundwater contribution to springs and other GDEs

The groundwater component of the Reserve is defined by the following relationship:

$$Reserve(\%) = \frac{EWRgw + BHNgw}{Re} \times 100$$

Where

R*e*	=	recharge
BHN_{gw}	=	basic human needs derived from groundwater
EWR_{gw}	=	groundwater contribution to EWR

The Reserve is a subset of the Stress Index and does not take water use other than EWR into account. It is the only water use that is legally protected and does not require authorisation.

Groundwater can only be allocated to users and potential users once the volume of groundwater that contributes to sustaining the Reserve has been quantified and RQOs have been met. (Please note that RQOs can be based on **both** the Reserve and Classification)

The challenge for the geohydrologist is to establish the relationship (spatially and temporally) between the volume of water that can be abstracted without impacting on the Reserve (and other GRDM) requirements.

Key Note: Groundwater allocation

The Groundwater Allocation is that volume of groundwater that can be allocated for use after consideration of the Reserve and RQOs. The Groundwater Allocation has to be assigned to international obligations, Schedule 1 usage, General Authorisations and Existing Lawful Users before new license applications can be considered, taking social and economic considerations into account.

7.5.2.1 Recharge

Recharge is defined as the addition of water to the zone of saturation. Generally, this only includes contributions from precipitation, but penetration into the subsurface from rivers, dams and wetlands can be substantial under specific and normally localised conditions. Aquifers can also be recharged by inflow from adjacent groundwater bodies.

Recharge is one of the most important parameters in assessing the sustainable volume of groundwater that can be abstracted from an aquifer system. Unfortunately, it is also difficult to quantify because of rainfall variability and aquifer heterogeneities. It is beyond the scope of this training manual to provide training in methodologies used to quantify recharge, as this requires a high level of geohydrological expertise and judgement. However, guidance is given regarding where information can be obtained and which tools can be used for estimating recharge.

As a start, the national scale map of recharge prepared by Vegter (1995) (Figure 7.1) can be used to obtain an indication of recharge; while work by Kirchner et al. (1991), Parsons (1993, 2000), Bredenkamp et al. (1995), Woodford and Chevallier (2002), Sami (2003), Xu and Beekman (2003) and others provides estimates of recharge in various parts of the country. It is the geohydrologists task to provide the best possible estimate of recharge within the scope and level of GRDM assessment being undertaken.

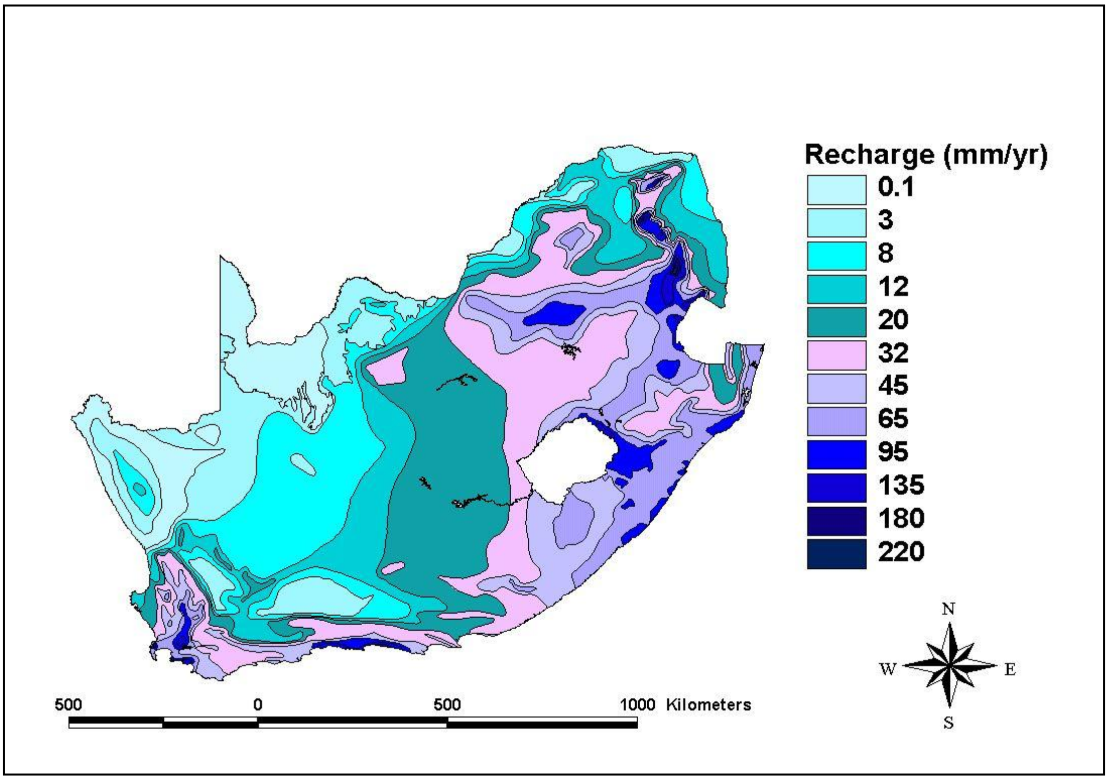


Figure 7.1: National scale map of recharge prepared by Vegter (1995)

In some instances, reserving the volume of groundwater discharged at surface is inadequate for ensuring that groundwater-dependent ecosystems are protected. Examples of this include wetlands, groundwater-dependent vegetation and the strip along the coast that is vulnerable to saline intrusion. By creating a protection or exclusion zone around these areas in which abstraction is prevented or restricted, the ability of groundwater to sustain these systems can be protected. However, it may become necessary during an assessment to consider the need for expanding protection or exclusion zones to ensure that a positive water gradient can be maintained.

Sensitive ecosystems need to be delineated (in consultation with an appropriate specialist) and the area of the protection zone around them calculated. Methods for doing so are addressed in section 8 and included in the GRDM Software. The total area of the groundwater resource unit is reduced by the area of the protection zone to yield an effective area of the groundwater unit.

In addition to reducing the area of resource units, groundwater abstraction from a protection zone can be prevented or restricted. This approach forms part of setting RQOs (Chapter 7.6).

7.5.2.2 Groundwater inflows and outflows

Quantification of the Reserve might require that groundwater inflows and outflows be calculated in addition to recharge from precipitation. While often small in relation to recharge to a quaternary catchment, subsurface inflows and outflows may be significant when dealing with smaller groundwater resource units or when dealing with artificial recharge. When undertaking desktop or rapid GRDM assessments, the quantification of recharge may suffice. However, when undertaking more detailed assessments, consideration of subsurface inflows and outflows is required. Methods for calculating inflows and outflows are described in section 8 and are included in the GRDM Software.

Examples would be the dolomitic aquifers and the sandstones of the TMG.

7.5.2.3 Basic human needs

Currently, basic human needs (BHN) are set by the WSA at 25 ℓ/pppd. The source of population statistics used for this calculation must be clearly referenced.

Although normally quite small in comparison to other uses, it must be borne in mind that this one of rights to water that must be legally protected.

7.5.2.4 Groundwater contribution to Ecological Water Requirements

Although the NWA only stipulates that river ecology should be maintained, the NWRS has included terrestrial ecosystems as well. In order to meet these requirements, the EWRs that should be met have been expanded to include these components as well. Where applicable, the following groundwater contributions must be stipulated:

- baseflow to rivers
- baseflow to wetlands
- springs
- GDEs

7.5.2.4.1 Groundwater contribution to baseflow in rivers

The GRDM Assessment Software includes a baseflow separation routine using the Herold method (Herold, 1980) and requires monthly flow data to determine the groundwater component of baseflow. While geohydrologists should be able to address the groundwater contribution to baseflow, it is strongly recommended that this be done in consultation with an experienced hydrologist. In many instances the records obtained from DW&EA for flow gauging stations are very inaccurate at low flows (critical for baseflow separation) since the stations were never designed to measure low flows. The geohydrologist can use the GRDM Software for desktop or rapid assessments, but hydrological input must be obtained for intermediate and comprehensive assessments. Typically, the low maintenance baseflow determined by the specialists undertaking the river quantity component of the Reserve assessment can be used in the GRDM assessment as a good indicator of the groundwater contribution to baseflow. Experience gained since the NWA has been promulgated has shown that the groundwater contribution to baseflow is much smaller than initially anticipated. The software must therefore be used with caution.

There are currently no techniques to assess the groundwater contribution to flow that supports wetlands or GDEs primarily because flow gauging stations are non-existent in these instances. The assessment would therefore be qualitative, but protection measures should be built into the RQOs where they occur. For example, if a few low-yielding springs in a small area have been shown not to be impacted by groundwater abstraction, then a current classification of ‘I’ may be appropriate. If the springs were to dry up and significantly impact sensitive ecosystems, a ‘II’ or lower category might be assigned.

If flow data are not available or unreliable, the following approach can be used to assess the groundwater contribution to baseflow and the quantification thereof:

Using Figure 7.2, assess whether the baseflow in a river is likely to be fed by groundwater. Ephemeral or highly seasonal streams and those streams with a low baseflow index are unlikely to be groundwater fed.

If the river has a low probability of being groundwater-fed, then no further assessment of baseflow is required.

If the river has a moderate to high probability of groundwater sustaining baseflow (perennial rivers with a moderate to high baseflow index, say above 0.2), then the maintenance low flow values, as determined by an experienced hydrologist, is required.

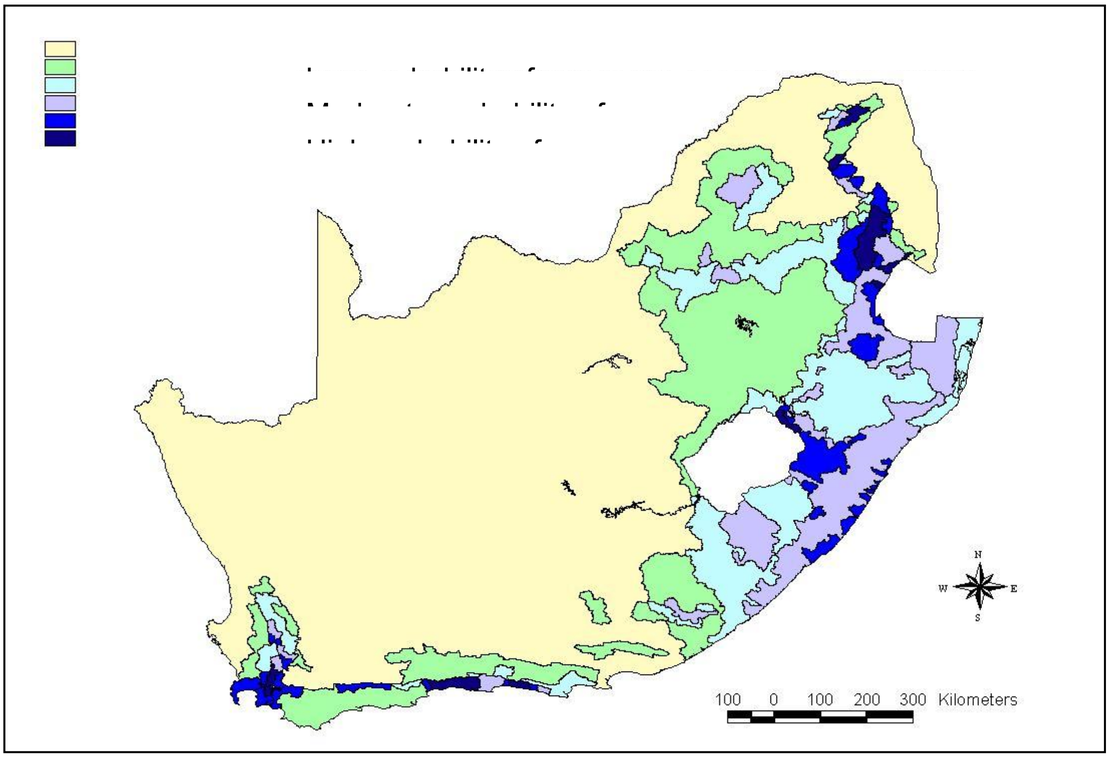


Figure 7.2: National scale map showing the relative probability of groundwater contributing to baseflow

Possible groundwater contribution to wetlands and GDEs should be assessed through field studies and with the aid of other relevant specialists.

7.5.2.4.2 Groundwater contribution to wetlands

The quantification of the groundwater contribution to wetlands is complex. It will be a function, amongst others, of the landscape location, vegetation, land use, as well as geology. The most common landscape locations where groundwater could play a role are the following (Chapter 5.2.2):

- **Slope wetlands**

Groundwater contribution to slope wetlands is most probably structurally controlled. Once the link between the wetland and the geology has been established and incorporated into the Reserve assessment it can be addressed through RQOs to ensure protection.

- **Valley bottom wetlands**

Valley bottom wetlands can be treated the same way as the groundwater contribution to baseflow in rivers.

- **Depression wetlands**

These are most probably geologically controlled and indicative of an aquitard near surface.

- **Coastal wetlands**

Coastal wetlands are fed from superficial deposits underlain by impervious material.

The groundwater contribution to wetlands will only be considered in detail during comprehensive studies where the protection of the wetland is crucial due to a possible unacceptable level of anthropogenic impacts. At more rapid assessments, a possible groundwater component needs to be identified qualitatively so that it can be incorporated into RQOs.

7.5.2.4.3 Groundwater contribution to springs

Many springs are structurally or geologically controlled, and these parameters need to be assessed in detail to ensure that protection measures are built into the RQOs.

7.5.2.4.4 Groundwater contribution to terrestrial ecosystems

It would be almost impossible to quantify a groundwater contribution to terrestrial ecosystems. Their presence need to be confirmed and protection measures will have to be tailored to the prevailing circumstances. The most important parameter to quantify or monitor would be the water level.

7.5.3 Key outcomes

The key outcome of this phase of GRDM is to determine the groundwater Reserve requirements which relate to BHN and EWRs. The allocation for each IUAs can be assessed without taking the requirements of Classification into account.

7.6 Resource quality objectives

The purpose of this phase is to:

Define RQOs for each resource unit

Relate the RQOs to management objectives

7.6.1 Purpose of Resource Quality Objectives

The purpose of the RQOs is to establish clear goals relating to the sustainable use of the relevant water resource. When setting 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 RQOs have been determined and gazetted, they are binding on all authorities and institutions when exercising any power or performing any duty under this Act. (Colvin et al, 2004). RQOs are used to put a Classification and Reserve into practice by specifying conditions that will ensure that the Class and is not compromised and the Reserve can be met.

RQOs are undoubtedly the most important outcome of the GRDM process, since this is the implementable component that should seamlessly guide the next phase, namely water allocation. Although allocation should consider equity and efficiency as well, goals set by RQOs should ensure that the resource is managed in a sustainable manner regardless other objectives that must be considered during the classification process.

7.6.2 What are Resource Quality Objectives

From the NWA: Resource Quality Objectives

Under Section 13.3 of the NWA, RQOs may relate to:

the Reserve;
the instream flow;
t**he water level;**
the presence and concentration of particular substances in the water;
the characteristics and quality of the water resource and the instream and **riparian habitat**;
the characteristics and distribution of aquatic biota;
the regulation or prohibition of instream or **land-based activities which may affect the quantity of water in or quality of the water resource; and any other characteristic of the water resource in question.**

Note: RQOs in **bold** relate directly to groundwater.

RQOs must set objectives for the management of water resources in a catchment (or other IUAs, if applicable) and by its very nature be applicable on that scale. RQOs should spell out the principles upon which WAP and licensing conditions are based. In general terms, RQOs establish clear goals relating to the quantity and quality of a water resource. They provide goals and objectives that frame the vision for sustainable use of a water resource, and hence form the basis for catchment decision-making and management.

It is very important to realise that they are applicable on a **catchment level** and is therefore fairly broad based. However, they must give guidance to conditions required in allocation plans and license conditions.

Typical characteristics of RQOs include:

- They set limits that are simple and measurable.
- They set the limits of acceptable impact.
- They may be numeric or descriptive.

RQOs should be set in consultation with stakeholders considering the catchment visioning process, and must give guidance to catchment management strategies, WAPs, source-directed controls, land-use planning and licensing conditions (adapted from Colvin et al., 2003).

7.6.3 Setting Resource Quality Objectives

In this manual RQOs will only be considered from a groundwater quantity perspective, since groundwater quality is addressed under SDCs.

Setting RQOs requires an understanding of groundwater resources and their boundary conditions, uses of groundwater, the importance of various uses and the agreed degree of modification of the resource (Colvin et al., 2003) as measured through the Stress Index. When setting RQOs, consideration must also be given to ecological dependencies on groundwater and the consequences of modifying the geohydrological regime. Setting RQOs also requires a detailed understanding of the Classification Process, since this formulates the parameters on which RQOs should be based. (RQOs related to Reserve is fairly clearly defined and limited, although very important). It is crucial that RQOs to be directly linked both Classification and Reserve to ensure their legal position in the event of disputes. If the MC is developed knowing that the outcome should really be in the form of a set of RQOs, it will focus this process.

It must be noted that the rules as specified in Fig 7.1 relates to the particular issue and does not prescribe the exact detail of its applicability on a very local scale. This is exactly what RQOs should achieve.

In essence, RQOs should ensure that the **integrity** of the resource is not compromised beyond a level of sustainability. This is graphically illustrated in Figure 7.1 to 7.3 (Parsons and Wentzel, 2007). The original illustration has been manipulated to reflect the author’s approach to groundwater integrity. It must be noted that the rules, as specified in Figures 7.1 to 7.3 relate to particular groundwater integrity issues and does not prescribe the exact detail of its applicability on a very local scale.

Groundwater System Integrity

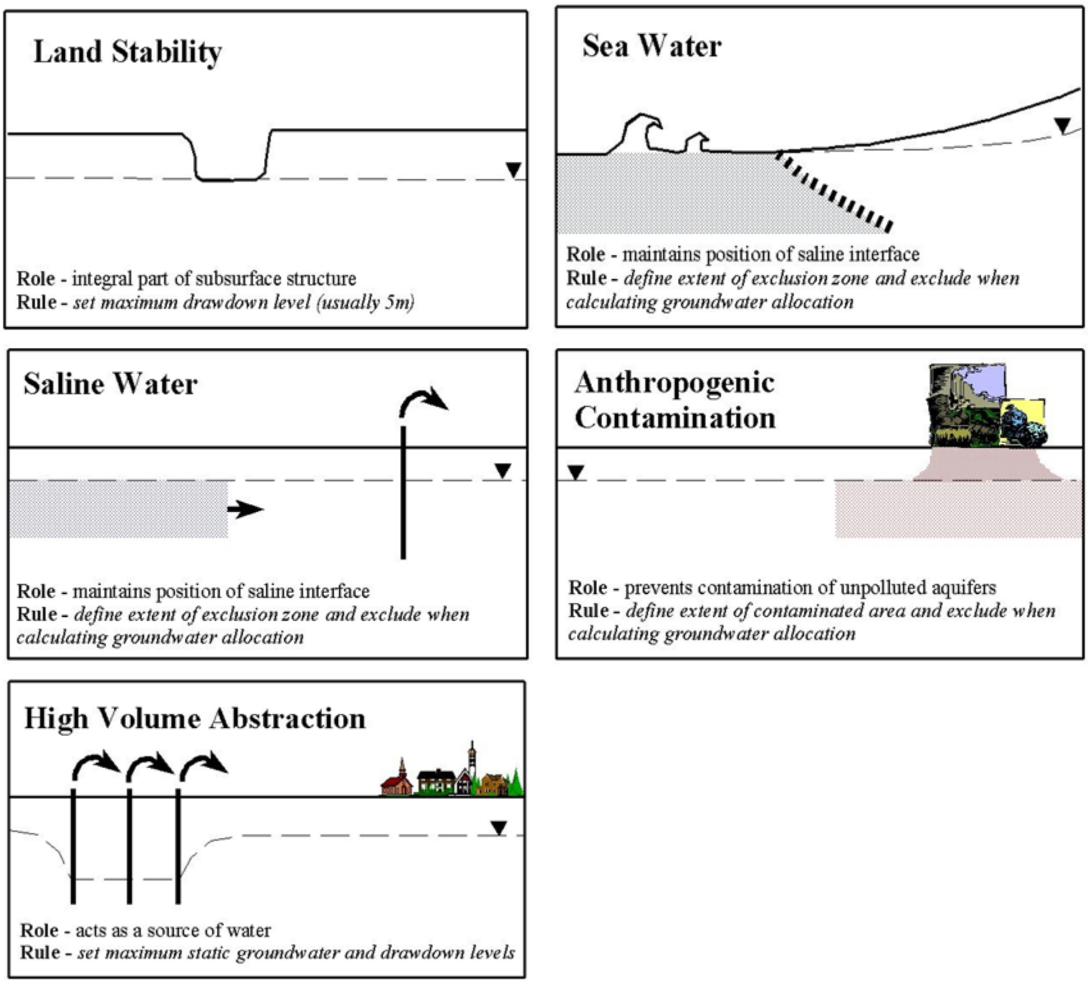


Figure 7.1 Groundwater System Integrity (Adapted from Parsons and Wentzel, 2007.

System Integrity can only be addressed through Classification, since there is no mechanism in the Reserve to address this crucial issue. Although the NWRS stipulates that groundwater quality issues be dealt with under SDCs, system integrity would at least ensure that the ambient water quality of the groundwater resource is not impacted upon on a regional scale.

The following should be considered:

- Geology in relation to possible subsidence
- Demography in relation to possible pollution
- Proximity to coastline
- Assessment of regional water table

Ecological Integrity

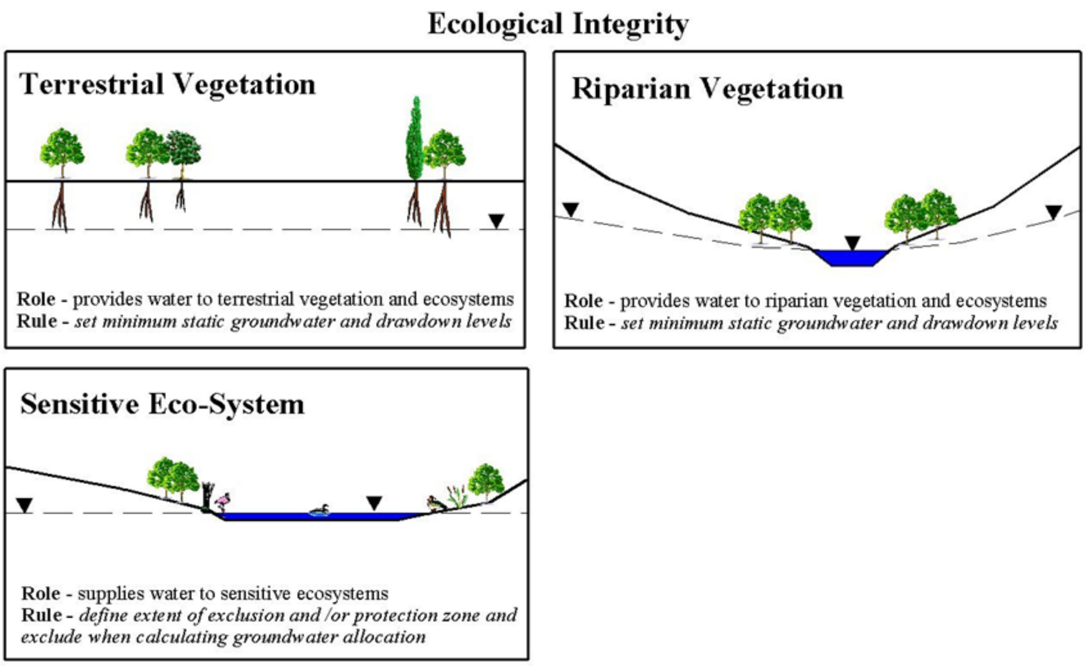


Figure 7.2 Groundwater ecological integrity (Adapted from Parsons and Wentzel, 2007)

Ecological integrity can be assured under the Reserve, as required by the NWA.

Apart from groundwater contribution to baseflow that has already been discussed in detail (Chapter 7.5), the following must be evaluated:

- Plant communities and their temporal water requirements
- Structural geology
- Soil types
- Water quality

Discharge Integrity

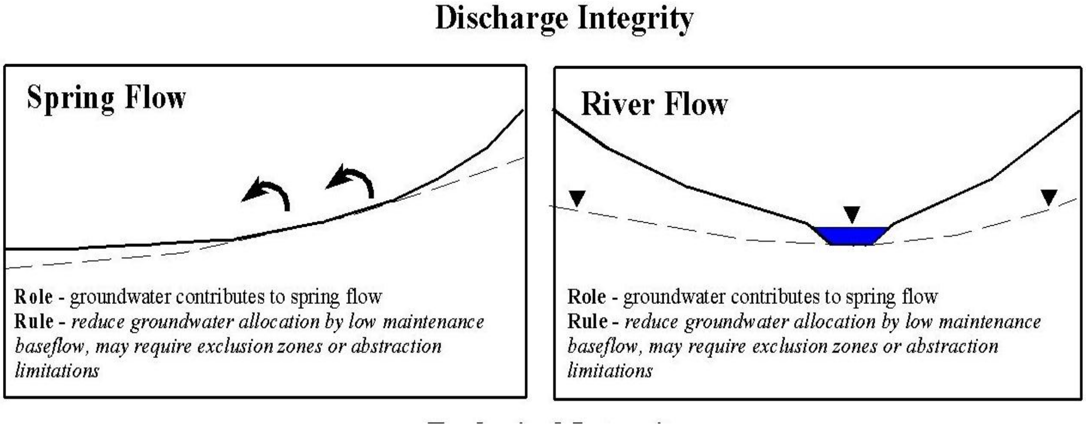


Figure 7.3 Groundwater discharge integrity (Adapted from Parsons and Wentzel, 2007)

Discharge integrity can be assured under the Reserve, as required by the NWA.

The following should be considered:

- Regional water table
- Structural geology

7.6.7 Procedure for setting RQOs

> **Key Note: Characteristics of good environmental indicators**
>
> Have an agreed, scientific meaning
>
> Represent an environmental aspect of importance to society
>
> Its meaning is readily understood
>
> It has a sound and practical measurement process
>
> Helps focus information to answer important questions

The setting of RQOs must be based on the conceptual understanding of groundwater resource units, the class of the resource that has to be sustained (Chapter 7.4) and the Reserve that has to be met (Chapter 7.5).

The process is graphically illustrated in Figures 7.4 and 7.5. The classification process has two legs – ecological and other consumptive uses. From an RQO perspective, they cannot really be separated since both constitute water uses that have to be met from the same resource, but for the sake of argument, they will be treated separately. The only difference is that the Reserve requirements must first be met before other requirements can be considered.

7.6.7.1 Consumptive use

In this sense the term is used to exclude all ecological consumption, hence the RQOs are totally dependant on Classification and specifically the SI.

For instance, if the MC is moderately used (II), the maximum amount of water that can be allocated in the **catchment i**s 40% (less EWRs and BHN, if applicable, see Table 8.1). This amount must be spread over the catchment where water use occurs. In many instances, it is unlikely that this will be evenly spread or required across the catchment and therefore the condition can be adhered to. However, when the Resource is a sole source aquifer, additional mechanisms may be required to ensure availability of water for human consumption. The most obvious condition is the element of risk of failure and that can only be assessed on a very local scale. The detail need not be captured in a RQO, but the guiding principle must be stipulated. If the resource has more than one use, for instance irrigation and Schedule 1 use, the latter must be safeguarded via the setting of RQOs.

7.6.7.2 Ecological water requirements

Ecological Water Requirements can be divided into two components:

Baseflow requirements in rivers

This parameter would normally be quantified in the Reserve process (see Ch 7.5). What needs to be assessed in RQOs is how it should be implemented. Depending on the rock type (i.e. transmissivity), water level and recharge, it can either be set as a water level or gradient that should ensure that groundwater still contributes to baseflow, or/and as an exclusion zone.

For example, the RQO would state that the water level may not be drawn down to such an extent that the baseflow be impacted (spatially and temporally). The licensing condition (applicable to a particular site) would state that the water level 100m from the river may not drop below 5 mbgl during the period May to September. Another site with a different geomorphology could apply the same RQO but state that the water level may not drop below 10mbgl 300m from the river and that no abstraction should be allowed with 200m from the river.

Requirements for wetlands and GDEs

The wetlands dependent on groundwater as well as GDEs are discussed in Ch 6. Again, the most important considerations would be a water level and/or an exclusion zone as well as a gradient.

A typical RQO could state that the water level upstream of the wetland may not be dropped to a level lower than the highest point of the wetland. If the rock in the area is quartzitic, an exclusion zone of 500m is applicable. The licensing condition emanating from this might state that at a contour level of 1200 masl at coordinates 27.1234S 27.2345E the water level may not drop to more than 5mbgl during the winter and not more than 8mbgl in summer. No abstraction to take place in a radius of 500m around the above coordinate.

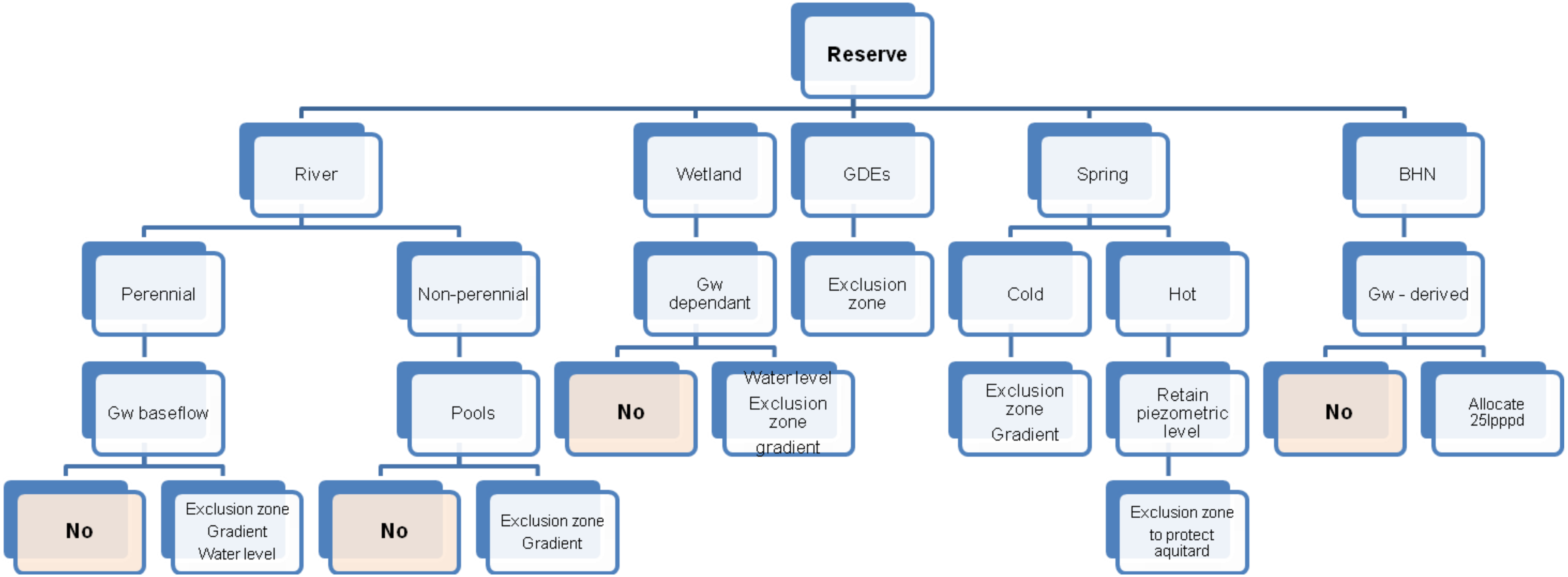


Figure 7.4 Flow diagram illustrating RQO concepts

RQOs based on Ecological, as well as Discharge Integrity, including the Reserve

Baseflow requirements in rivers

These RQOs should ensure that the Ecological Integrity of the resource is not compromised.

Groundwater contribution to baseflow is quantified in the Reserve process (see Chapter 7.5). What needs to be assessed in RQOs is how this should be implemented.

In the case of perennial rivers and depending on the rock type (i.e. transmissivity), water level and recharge, RQOs can either be set as a water level that should ensure that groundwater still contributes to baseflow, and or/ as an exclusion zone.

In the case of non-perennial rivers, the identification of pools fed by groundwater becomes very important. They sustain refugia in the dry season that populate the river when it starts flowing again. An RQO in this instance would have a temporal as well as a spatial component. For example, an RQO could state that the water level may not be drawn down to such an extent that the baseflow is impacted (spatially and temporally). The licensing condition (applicable to a particular site within the catchment) would state that the water level 100m from the river may not drop below 25mbgl during the period from May to September. Another site with a different geomorphology could apply the same RQO, but state that the water level may not drop below 10mbgl 300m from the river, and that no abstraction should be allowed within 200m from the river.

Requirements for wetlands

The wetlands dependent on groundwater, as well as other groundwater dependent ecosystems, (GDEs) are discussed in Chapter 6. Again, the most important consideration is a water level/gradient and/or an exclusion zone.

A typical RQO could state that the water level upstream of the wetland may not be dropped to a level lower than the highest point of the wetland.

Most wetland plants are sensitive to water quality and this must be considered when setting RQOs.

The author is not aware of any current methodologies that can assess this on a regional scale. If detailed data are required this will have to be obtained from a carefully planned drilling programme around the wetland. A contour map of the area would assist in setting the required water level and gradient to be maintained towards the wetland.

The licensing condition emanating from this might state that, at a contour level of 1200masl at coordinates 27.1234S 27.2345E, the water level may not drop to more than 5mbgl during the winter and not more than 8mbgl in summer. No abstraction should take place in a radius of 500 m around the above coordinates.

Groundwater dependent ecosystems

GDEs should be approached in the same way as pools in non-perennial rivers, but each case will have to be assessed by an expert in the field. An RQO in this instance would have a temporal as well as spatial component. The most important parameter in this instance would be a water level that in turn would be determined by the type of vegetation in the GDE.

Requirements for springs

Most springs are structurally controlled and generic guidelines for their protection are problematic.

In the case of cold springs, the structural geology would most likely be the key controller. Once the origin of the spring has been established, the RQOs should ensure that the structural integrity of the resource is not compromised. It could be in the form of an exclusion zone around the spring or a water level. It must be noted that factors that can affect the spring may be quite some distance away.

Hot springs are structurally controlled on a regional scale, and their protection measures should incorporate this. In most cases, it would suffice if the piezometric pressure of the spring is retained.

Basic Human Need Requirements

Currently the BHN requirements are set at 25 ℓ/person/day. It needs no expansion in RQOs, since it is a compulsory requirement of the Reserve. It must, however, be taken into account when the SI is determined.

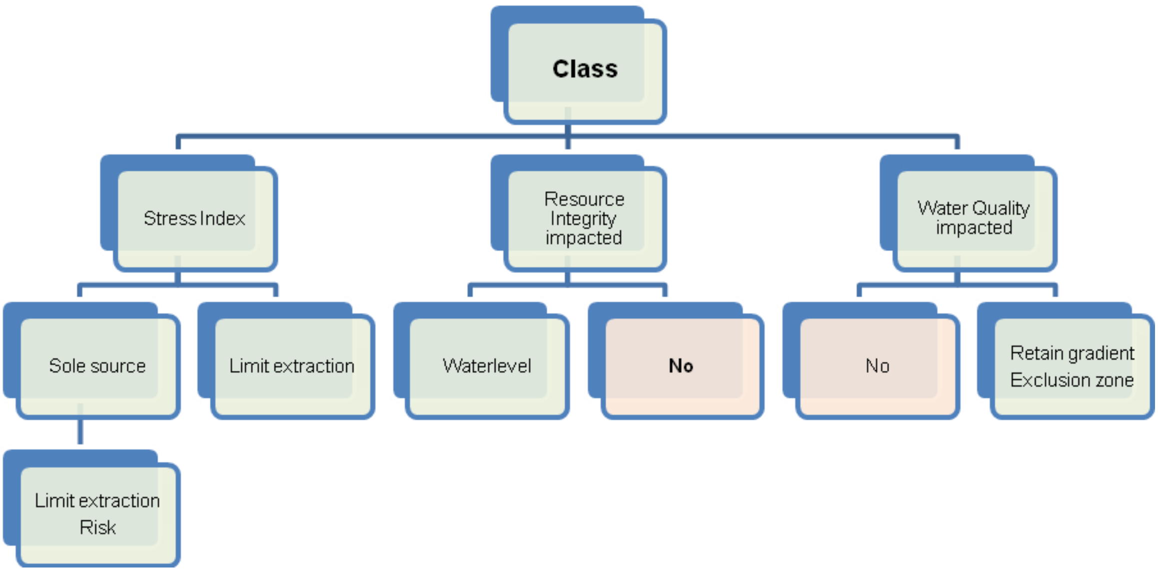


Figure 7.5 Flow diagram illustrating RQO concepts

RQOs based on Classification

RQOs based on Classification should be approached from a Resource Integrity perspective.

System Integrity

System Integrity can be related to the SI (Table 10.4).

For instance, if the MC is moderately used (II), (see Table 10.1) the maximum amount of water that can be allocated in the **catchment** is 40% of Recharge (less EWRs and BHN, if applicable). This amount must be distributed over the catchment where water use occurs. In many instances, it is unlikely that this distribution will be evenly spread or required, and therefore the condition can be met. However, when the resource is a sole-source aquifer, additional mechanisms may be required to ensure water availability for human consumption. The most obvious condition is the element of risk of failure and can only be assessed at the point of impact. The details need not be captured in a RQO, but the guiding principle must be stipulated. If the resource has more than one use, for instance irrigation and Schedule 1, the latter must be safeguarded in setting RQOs.

System Integrity is normally compromised by over-abstraction. Structural Integrity is linked to geology. In the South African sense, this is mainly related to dolomitic aquifers where he input of a specialist is required to assess the aquifer integrity. If it is suspected that it can be compromised by abstraction permissible under the Stress Index, the resultant RQO would probably stipulate an ambient water level that must be maintained, as well a maximum drawdown that could be allowed.

Water quality impacts

Water quality in a system can be compromised by anthropogenic activities and over-abstraction. Once again, the dolomitic aquifers in particular are very vulnerable. Coastal aquifers where saline intrusion may occur in the event of over-abstraction are also important in this regard. Due to the high permeability of these aquifers, they are also susceptible to anthropogenic impacts.

RQOs would include retaining a positive gradient and local drawdown limits to ensure that intrusion does not occur. An exclusion zone could be a first measure to ensure that a positive gradient is maintained.

Possible anthropogenic impacts, such as pit latrines and graveyards, must be isolated from abstraction points.

Special Case: Mining impacts

As mines are shut down and groundwater abstraction from the mine is reduced or halted, some mining areas in South Africa are experiencing rising groundwater levels as the levels revert back to their pre-mini*Set class oVision for the resource*

us environmental consequences since it is accompanied by acid rock drainage. It is too late now to stipulate RQOs and the only solution is remedial. This is exactly the type of

7.7 Key outcomes

The key outcome of this phase of the GRDM assessment is a list of practical and implementable RQOs that can be translated into an Allocation Plan or licensing conditions that can be monitored to ensure that the Classification of the groundwater unit is not compromised and that the ability of the groundwater system to sustain the Reserve is not impaired.

It is pointless to develop a set of objectives that cannot be implemented or monitored to check whether the objective can be met. Each RQO should be defined in terms of:

The resource attribute value, e.g. groundwater level, a specific water quality parameter

- The location or area of groundwater management to which it should apply
- Acceptable temporal and spatial range of values
- Frequency and density of monitoring to ensure compliance.

8 METHODS, TOOLS AND DATA USED IN THE SOFTWARE

This section describes some of the tools and methods that can be used to quantify various components of GRDM. A summary of methods and tools is presented in Table 8.1 at the end of the chapter. While undertaking a GRDM assessment requires a degree of experience and expert knowledge, new tools and methods are constantly being developed to address the challenges of the day. It remains the responsibility of the geohydrologist undertaking a GRDM assessment to use appropriate tools, methods and supportive software packages.

8.1 Quantifying recharge

Recharge remains one of the critical parameters to determine in all geohydrological studies, and is one of the most difficult to quantify. Kirchner et al. (1991), Giekse (1992), Bredenkamp et al. (1995) and Xu and Beekman (2003) provide good descriptions of methods that can be used to quantify recharge. Usually the method used to quantify recharge is dependent on the data available on which to base the assessment. It is recommended that more than one method be used.

- Recharge estimation tolls could include the following:
- recharge maps
- chloride mass balance method
- springflow technique
- hydrograph or baseflow separation techniques
- saturated volume fluctuation method
- water table function method
- cumulative rainfall departure method
- isotope-based methods
- EARTH model
- numeric groundwater flow models.

Some recharge estimation tools and techniques are discussed in detail.

8.1.1 Recharge maps

Two national scale maps of recharge are currently available. While preparing his geohydrological maps of South Africa, Vegter (1995) attempted to quantify recharge. Schulze (1997) prepared a similar map, but of the annual recharge of soil water into the vadose zone (Figure 8.1). While Figure 8.1 may not relate directly to the addition of water to the groundwater system below the water table, it supports the work by Vegter (1995). The map prepared by Vegter (1995) is used in the GRDM software to provide initial values of recharge to quaternary catchments.

Both maps are useful for obtaining a quick indication of recharge in a particular area. However, they must be used with caution. They provide only an indication of average recharge over an area and cannot be used to determine recharge on a local scale. Whenever possible, more detailed and site-specific information should be used.

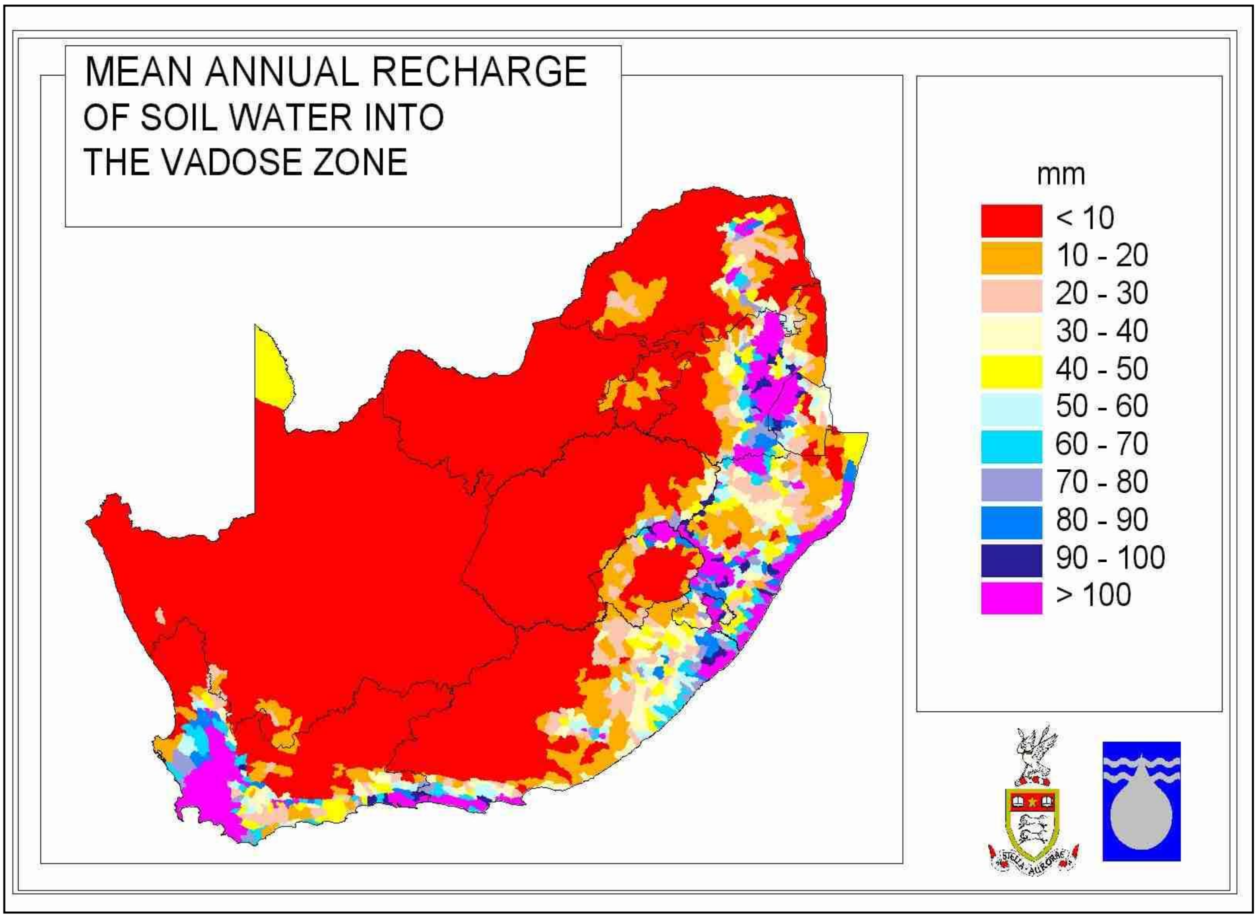


Figure 8.1: Recharge of soil water into the vadose prepared by Schulze (1997)

8.1.2 Chloride mass balance method

This method is based on the assumption of the conservation of mass between the input of atmospheric chloride and the chloride flux in the subsurface. Chloride is conservative by nature and hence is not readily precipitated out of groundwater by subsurface chemical reactions. The application requires a concentration of chloride in rainwater and in groundwater, as well as the mean annual precipitation in the area of interest. Recharge is calculated using the following relationship:

$$R_T = TD \times \frac{MAP}{Cl_{gw}}$$

Where:

R_T	=	total recharge (mm/a)
TD	=	total atmospheric chloride deposition (mg/ℓ)
MAP	=	mean annual precipitation (mm/a)
Cl_{gw}	=	harmonic mean of the chloride concentration in groundwater(mg/ℓ)

The chloride mass balance method has been used to evaluate recharge processes in a range of semi-arid environments. No sophisticated instrumentation or dependence on the measuring of specific runoff events is required. Also, estimates of recharge are independent of whether recharge is focused or diffuse. While easy to use and inexpensive, the method requires the concentration of chloride in rainfall. In addition to seldom being available, the low concentration of chloride in rainfall results in small differences in chemical analysis resulting in large differences in the computed recharge. For meaningful results, an accuracy and precision of 0.1 mg/ℓ chloride is required.

The method assumes that rainfall is the only source of chloride into the groundwater system. Where other sources of chloride exist (e.g. rocks deposited under marine conditions, mineralogical composition of rock contributes chloride to groundwater through dissolution or weathering, contamination etc.), the method becomes invalid and can no longer be used. The same applies near coastal regions where the chloride content of rainwater is abnormally high.

8.1.3 EARTH model

EARTH is an abbreviation for **E**xtended model for **A**quifer **R**echarge and soil moisture **T**ransport through the unsaturated **H**ardrock and is a curve-fitting procedure used to determine recharge at a single borehole. The general equation used in the model is:

$$S\frac{dh}{dt} = Recharge - \left(\frac{h}{DR}\right)$$

Where:

S = specific yield

dh/dt = change in water level head during one month

DR = drainage resistance (a site specific parameter)

h = groundwater level

Monthly groundwater level and rainfall data are required by the model, as is an estimate of the specific yield of the aquifer. While the method appears promising, it is doubtful that a simple averaging of groundwater recharge values from point locations irregularly scattered in heterogeneous fractured-rock aquifers will result in a reliable assessment of recharge across the aquifer.

8.1.4 Cumulative rainfall departure method

The Cumulative Rainfall Departure (CRD) method is a water balance approach and is based on the premise that groundwater level fluctuations are caused by rainfall events (Figure 8.2). Bredenkamp et al. (1995) applied the method successfully in South Africa.

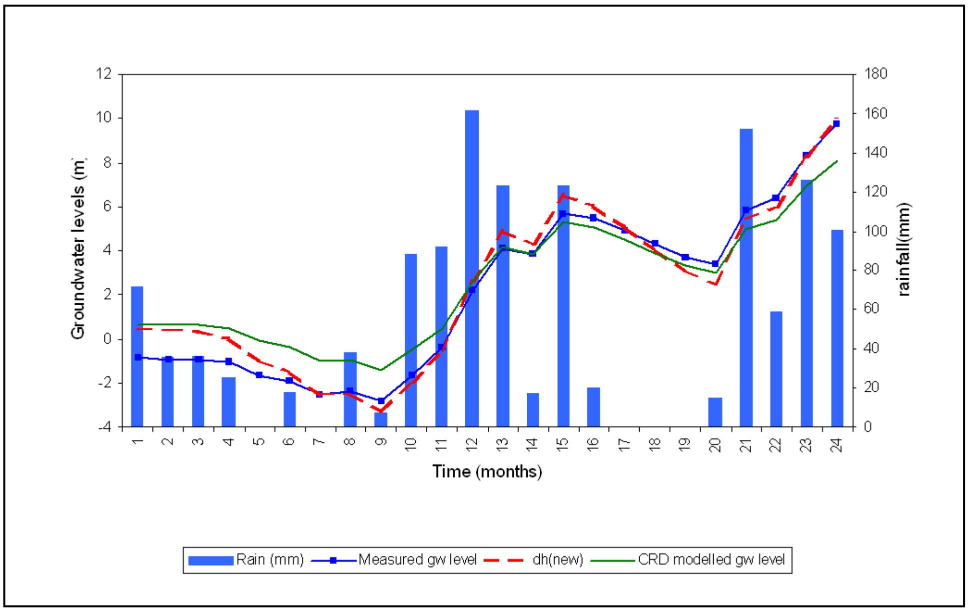


Figure 8.2: An example of the outcomes of the CRD method used to estimate recharge

The method provides an integrated average recharge value. It also provides a useful tool with which to generate groundwater level or spring flow data missing from monitored records. The method requires monthly rainfall and groundwater level data, as well as information pertaining to aquifer properties (storativity), abstraction and the size of the recharge area. The CRD method cannot be applied in areas with no or very small groundwater level fluctuations.

8.1.5 Saturated volume fluctuation method

The saturated volume fluctuation (SVF) method incorporates a lumped parameter approach taking in account aquifer water levels, abstraction from the aquifer and natural flow (Figure 8.3). Bredenkamp et al. (1995) applied this method successfully in South Africa. The general equation used to determine recharge is:

$$h_i = h_{i-1} + R_i/S + (I_i - O_i)/SA - Q_o/SA$$

Where:

h_i = head at month i (m)

h_{i-1} = head at previous month

R_i = recharge in month i (m)

I_i, O_i and Q_o = inflow, outflow and abstraction in month i (m^3/month)

A = area of aquifer (m^2)

S = specific yield

A good spatial distribution of boreholes is a prerequisite for the successful application of this method.

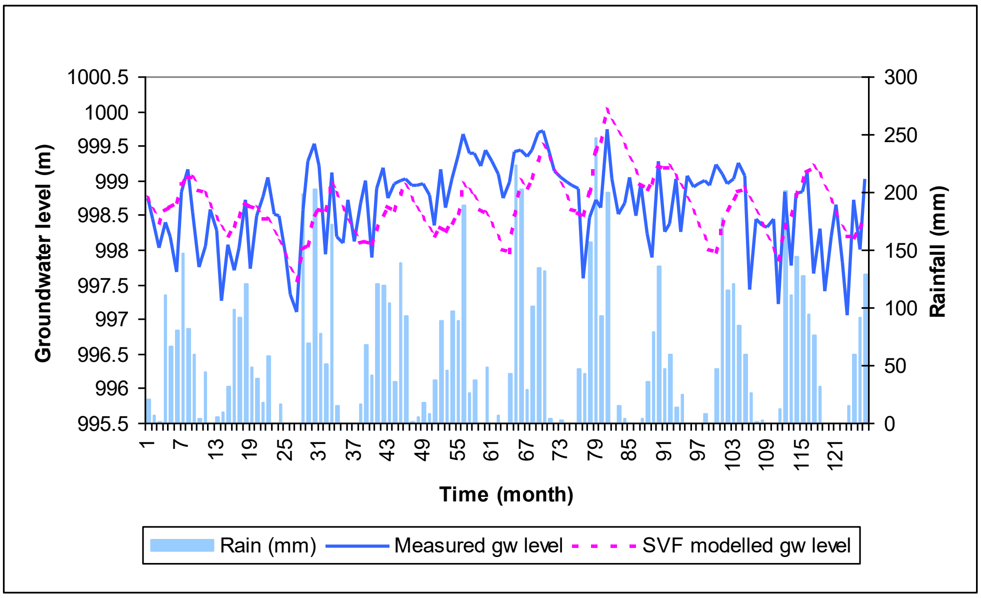


Figure 8.3: An example of the outcomes of the SVF method used to estimate recharge

8.1.6 Isotopes

Oxygen-18 and deuterium are naturally occurring stable isotopes of oxygen and hydrogen. Moisture fluxes or recharge estimates may be derived from a relationship between $^{2}\delta$ displacements of isotopic compositions of soil moisture from the local meteoric line and the inverse of the square root of recharge. It has been determined that in a $^{18}\delta$ - $^{2}\delta$ plot, the displacement of soil moisture is represented by a line parallel to the local meteoric water line (MWL) and is proportional to the inverse of the square root of the recharge rate.

The amount of displacement from the local MWL is controlled by a balance between the isotopic enrichment attained in the upper layers of the soil (due to evaporation) and dilution of this isotopic enrichment by rainfall. The following equation can be derived assuming that the number of rainfall events is proportional to the total recharge:

$$\Delta\delta = \frac{C}{\sqrt{Recharge}}$$

The constant C represents the slope of a line through the inverse of the square root of recharge rates obtained from other recharge estimation methods. In South Africa the equation used to determine the recharge is:

$$\Delta\delta = \frac{20}{\sqrt{Recharge}}$$

It is important to note that this method is only applicable if recharge is less than 20 mm/a.

8.1.7 Numerical groundwater flow models

The aim of groundwater modelling is to predict aquifer piezometry under different conditions, and as a result can be used to estimate recharge. Models are essentially sophisticated water balance methods that attempt to balance input, storage and output from an aquifer system.

When developing numerical models, the user creates a regular grid over the area to be modelled that subdivides the total model area into cells. Parameters, such as water level, transmissivity and recharge are assigned to each cell. Calibration takes place by comparing observed field data to simulated data. Parameters such as recharge are adjusted until the simulated and observed water levels coincide and provide a high degree of correlation.

A wide range of numerical flow models is currently available, including Visual Modflow, PMWin and others. To be able to develop and calibrate the models, data pertaining to aquifer geometry, aquifer properties, groundwater levels and recharge are required. In general, the models are data-intensive, are time-consuming to develop and calibrate, and require a proficient groundwater modeller to produce meaningful results. Moreover, the numerical solutions are not unique and are dependent on the aquifer parameters assigned in the model.

8.2 Quantifying other inflows and outflows

Darcy's Law can be used to approximate groundwater inflows into and outflows from groundwater units. Darcy's Law states that the rate of flow through a porous medium is proportional to the loss of head, and inversely proportional to the length of the flow path. The following equation can be used to calculate both inflows into and outflows from a groundwater unit:

$$Q = T\ i\ w$$

Where:

Q = discharge (m^3/d)

T = transmissivity (m^2/d)

i = groundwater gradient

w = width of groundwater unit perpendicular to flow (m)

Estimates of transmissivity are obtained from aquifer tests or can be approximated from prevailing geology or borehole yields. Transmissivity near a borehole can be estimated from the following relationship:

$$T = 10\ Q$$

Where:

Q = borehole yield in ℓ/s

The groundwater or hydraulic gradient can be determined from a groundwater level contour map or approximated from surface topography, while the width of the groundwater unit can be measured from the map showing the delineation of the units.

The flux across a unit boundary can be calculated using the water budget option in a numerical model.

8.3 Quantifying the groundwater contribution to baseflow

8.3.1 Baseflow maps

On the understanding that baseflow was an indication of the minimum recharge to an area, Vegter (1995) attempted to quantify the groundwater contribution to baseflow (Figure 8.3). The map is used in the GRDM Software and provides an initial indication of the groundwater contribution to flow in rivers. As it is now recognised that not all baseflow is derived from rivers, this map should be treated with caution, and more detailed and site-specific information should be used. However, it is extremely useful for a first order estimation that would exclude large parts of the country from assessment.

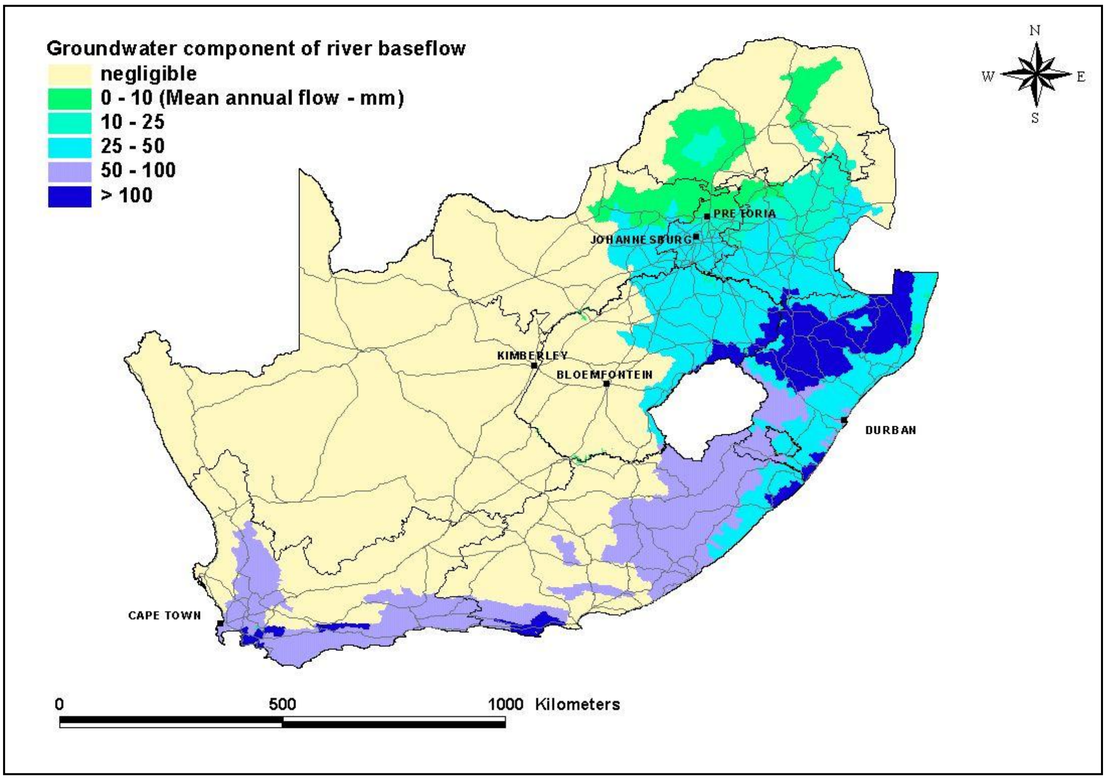


Figure 8.3: Estimation of groundwater contribution to river flow by Vegter (1995)

8.3.2 Herold method of baseflow separation

The Herold method (Herold, 1980) is used in the GRDM Assessment Software to determine the groundwater contribution to flow in a river. Vegter and Pitman (in Xu and Beekman, 2003) explained the Herold method as follows:

$$Qi = QGi + Qsi$$

Where:

Qi = total flow during month i

QGi = groundwater contribution

QSi = surface runoff

The assumption is made that all flow below a certain value (called GGMAX) is groundwater flow, hence:

$$QS_i = Q_i - GGMAX \quad (\text{for } Q_i > QGMAX)$$

Or $$QS_i = 0 \quad (\text{for } Q_i \leq QGMAX)$$

and hence $$QG_i = Q_i - Qs_i$$

The value of GGMAX is adjusted each month according to the surface runoff during the preceding month and is assumed to decay with time, hence

$$GGMAX_i = DECAY.GGMAY_{i-1} + PG.QS_{i-1}/100$$

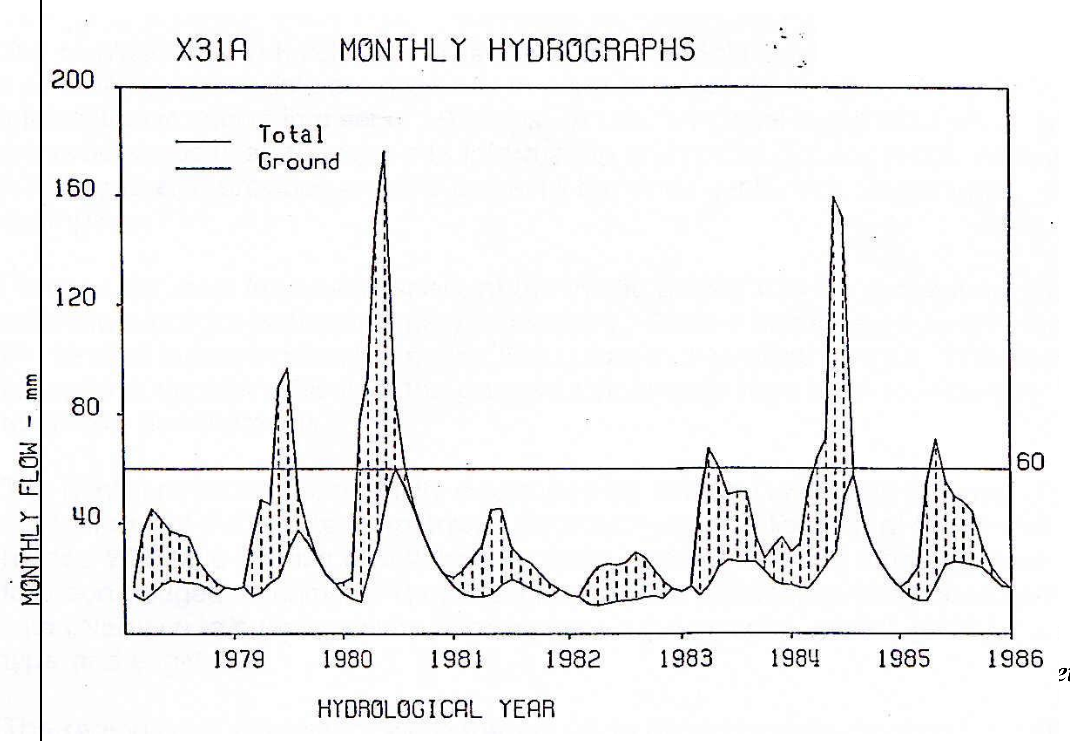
Where:

subscripts *i* and *i-1* refer to the current and preceding month.

DECAY = groundwater decay factor ($0 < DECAY < 1$)

PG = groundwater growth factor ($0 < PG > 1$)

An added constraint is that *GGMAX* may not fall below a specified value, *QGMAX*. Calibration of this model is achieved by selecting an appropriate value of *DECAY*, *PG* and *QGMAX* so that a realistic division between surface runoff and groundwater is obtained (Figure 8.4).



Monthly flow data are required for the separation process. Naturalised monthly flow data for each quaternary catchment can be obtained from WR90 while flow data can be downloaded from the DW&EA website (www.dwaf.gov.za). The method has been included in the GRDM Assessment Software and is easy to use. However, the fitting of the separation curve is subjective, and the user has to decide which is the most appropriate fit when trying to quantify the groundwater contribution to river flow. It is strongly recommended that the separation be done in consultation with an experienced hydrologist. Not all flow records are accurate at low flows and a hydrologist should be committed to assess. the validity of the flow record for this purpose. Nonetheless, when doing the separation, the following should be borne in mind:

Groundwater will contribute very little to the flow in those rivers with a low baseflow index, ephemeral or strongly seasonal rivers. Consequently, the modelled groundwater contribution to flow should be small.

Given that annual groundwater level fluctuations in a catchment are small in relation to the length or width of the catchment (and consequently that the hydraulic gradient varies very little), it is conceptualised that the groundwater contribution to flow in a river remains fairly constant. It is hence not possible that the groundwater contribution to flow will vary by orders of magnitude as suggested by conventional approaches to baseflow separation.

8.3.3 Darcy's Law

The groundwater contribution to flow in a river can be estimated using Darcy's Law, which states that the rate of flow through a porous medium is proportional to the loss of head, and inversely proportional to the length of the flow path. Assuming that groundwater is discharged into the river from both sides, the following equation can be used to calculate discharge into the river:

$$Q = T\ i\ 2w$$

Where:

Q	=	discharge (m^3/d)
T	=	transmissivity (m^2/d)
i	=	groundwater gradient
w	=	length of the river (m)

To be able to calculate the volume of groundwater discharged into a river, an estimate of transmissivity, the hydraulic gradient and the length of river into which the groundwater is discharged are required. The hydraulic gradient can be approximated from surface topography. Approximation of the transmissivity along the length of a river is far more difficult, as the hydraulic properties of fractured-rock aquifers can vary significantly over short distances. In addition to data from aquifer tests, transmissivity in the vicinity of a borehole can be estimated from the following relationship:

$$T = 10\,Q$$

Where:

Q = borehole yield in ℓ/s

T = transmissivity (m^2/d)

By determining the harmonic mean of T in a catchment, an indication of the lumped transmissivity can be obtained.

Estimating the length of river into which groundwater is discharged is also not as simple as it may seem. It is unlikely that the entire length of a river is effluent in character. Furthermore, it is likely that the lengths of river into which groundwater systems discharge vary seasonally. By preparing a groundwater level contour map of the groundwater resources and assuming that the river has an effluent character in those areas where the groundwater level is within (say) 2.5 m of the river bed, an approximation of the length of river can be obtained.

While the calculation of groundwater contribution using a Darcian approach may be simplistic in that it does not take into account the heterogeneous nature of most aquifer systems and localised variations in hydraulic properties, it does allow for an independent assessment against which the assessment obtained from baseflow separation can be compared.

8.3.4 Numerical groundwater flow models

The flux into a surface water body can be calculated using the water budget option of numerical groundwater flow models. Issues pertaining to models discussed in section 8.1.6 remain valid with respect to quantifying groundwater discharge into surface water bodies and are hence not repeated here.

8.3.5 Low maintenance flows

DW&EA (1999) proposed low maintenance flows be used to assess the groundwater contribution to baseflow. Low maintenance flows are determined in the RDM assessment process by the surface water specialists. In instances where rivers are not ephemeral and have a moderate to high baseflow index, this is considered a practical approach for an intermediate level assessment. However, a more considered approach is required for a comprehensive GRDM assessment, while the GRDM Assessment Software is adequate for desktop and rapid assessments.

8.4 Resource quality objectives

A number of tools and simple flow equations can be used when setting resource quality objectives. These include defining setback distances from line or point sources, quantifying drawdowns and determining the rate at which a borehole can be pumped so that it does not influence groundwater levels near protection zones.

8.4.1 Delineation of protection or exclusion zones

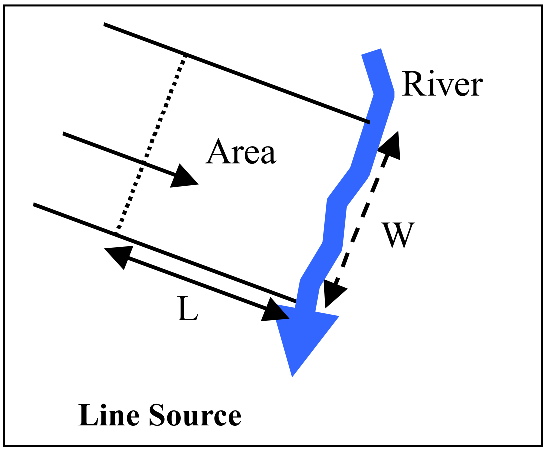


Figure 8.5: Determining the setback distance from a linear protection zone

Areas around sensitive ecosystems may need to be protected. This is done by delineating protection zones around them. The flux (Q_{ER}) necessary to maintain the ecosystem can be determined using either Darcy's Law (section 8.3.3) or a baseflow separation procedure (section 8.3.2). The protection area around a line source to be protected (such as a river) can be determined using Q_{ER}:

$$A = \frac{Q_{ER}}{R}$$

Where:

A = area to be protected (m^2)

Q_{ER} = flux (m^3/d)

R = effective recharge within the protection area (m/a).

The setback distance from the line source (L) can be calculated using:

$$L = \frac{A}{W}$$

Where:

L = length from source (m)

A = area of protection zone (m^2)

W = width of protection zone (m^3/d)

The protection area for a point source such as a wetland or a borehole used to supply basic human needs can be calculated in the same way as that of a line source, except that the length of the protection area (L) is calculated as follows:

$$L = \sqrt{\pi A}$$

Where:

L = length from the point source (m)

A = area of protection zone (m^2)

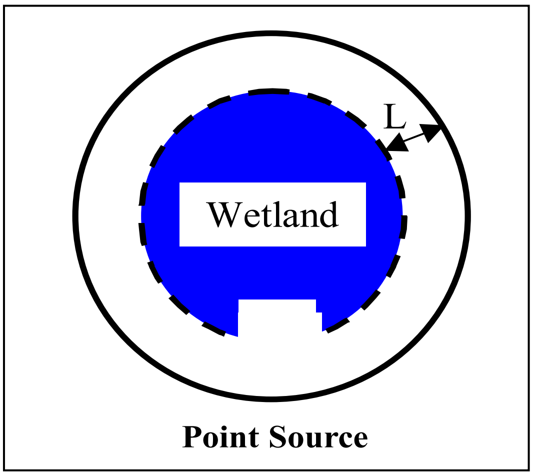


Figure 8.6: Determining the setback distance from a circular protection zone or point source

8.4.2 Calculating the radius of influence of a borehole

The maximum extent of the cone of depression – or the radius of influence (r_e) – of a borehole is independent of the rate of abstraction, but dependent on T, S and the duration (t) of abstraction. The radius of influence can be estimated using the following equation:

$$r_e = 1.5\sqrt{\frac{Tt}{S}}$$

Where:

T = transmissivity (m^2/d)

S = storativity

t = time (d)

If a borehole is pumped continuously, the radius of influence increases at a rate proportional to the square root of time, i.e. the radius of influence increases 30% each year.

8.4.3 Predicting drawdown as a result of abstraction

Many available methods can be used to predict the drawdown resulting from abstracting groundwater from a borehole. While use of numeric models allow for more sophisticated assessment (consideration of boundary conditions, assessment of the effects of pumping more than one borehole at a time, etc.), use of the Cooper-Jacob equation allows for a rapid calculation of drawdown-distance relationships when a borehole is pumped at a constant rate (Kruseman and De Ridder, 1991).

$$s = \frac{2.3Q}{4\pi T}\log\left(\frac{2.25Tt}{r^2 S}\right)$$

Where:

s = drawdown (m)

T = transmissivity (m^2/d)

t = time (d)

r = radius of borehole (m)

S = storativity

To be able to predict the drawdown in a borehole, information about the aquifer (transmissivity and storativity) is required, as is the radius of the borehole and the rate and duration of abstraction.

By rearranging the equation, it is possible to estimate the drawdown at some distance from the borehole. This is useful when setting RQOs relating to allowable drawdowns and set back distances.

8.4.4 Estimating allowable rates of abstraction

An exclusion or protection zone may be negatively impacted if abstraction from a borehole induces a cone of depression that extends into that zone, as indicated in Figure 8.x (b). It is possible to calculate the radius of influence that a particular abstraction rate will induce, as well as calculate the maximum rate of abstraction allowed in order not to impact a protection zone some distance away from the pumped borehole.

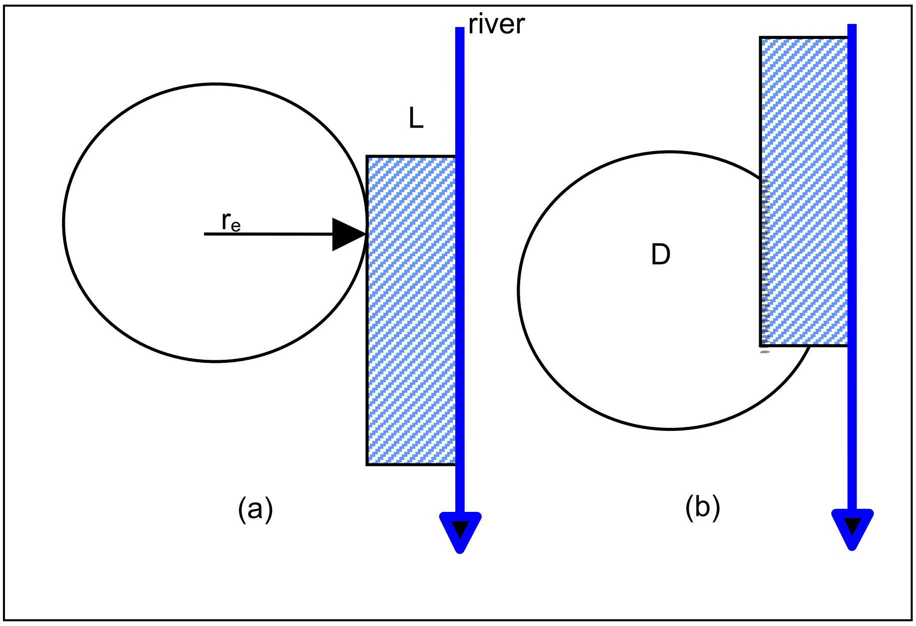


Figure 8.7: Graphical representation of the radius of influence (r_e) used to estimate the sustainable yield of a borehole (a) when the borehole does not influence the ecological protection zone and (b) when the borehole influences the ecological protection area

As indicated in Figure 8.7, in order for a borehole not to influence a water body, it should be located at least a distance $r_e + L$ from the body. If *D* is the distance between the borehole and the closest boundary of a protection zone and $D > r_e$, then abstraction from the borehole will not influence the protection zone. Conversely, if $D < r_e$, then abstraction from the borehole will have an influence on flow to the area. The rate at which a borehole can be pumped in order not to influence the protection – termed here as the *allocatable safe yield* of the borehole (Q_s) – can be calculated using the following equation:

$$Q_s = BR$$

Where:

Q_s = allocatable safe yield of *a* borehole (m^3/a)*, inside an area B (m^3)*

B = πD^2 if $D < r_e$

B = $\pi (r_e)^2$ if $D > r_e$

r_e = radius of influence after 365 days (m)

R = effective annual recharge (m/a)

When the distance between a borehole and the boundary of a protection zone is known (D), it is possible to predict the duration of pumping before the radius of influence will reach the boundary, i.e. where r_e = D:

$$t_d = SD^2 / (2.25T)$$

Where:

t_d = duration of abstraction before the r_e = D (days)

S = storativity

D = distance between borehole and boundary of protection zone (m)

T = transmissivity (m^2/d)

If, for some reason, a borehole is pumped at a rate greater than the determined allocatable safe yield, it is possible to estimate the maximum number of days per year that the borehole can be pumped at the actual rate of abstraction. It should be noted that during the period of abstraction, the radius of influence may extend into the protection zone.

$$t_d = (Qs / Q) \times 365$$

Where:

t_d = period of pumping allowed per annum (days) at a rate Q

Qs = allocatable safe yield (m^3/d)

Q = actual rate of pumping (m^3/d)

8.4.5 Borehole protection zones from on-site sanitation

Basic human need boreholes are important for many rural communities. However, the influence of pit latrines have to be taken into account as these are in most cases the only form of sanitation. There are two elements of concern in groundwater namely nitrates and microbial contaminants. Nitrates cause cyanosis due to methaeglobinemia, which is toxic to infants. Nitrate can also reduce to nitrite, which combines with haemoglobin (oxygen-carrying red blood cell) to form methaemoglobin. Methaemoglobin is incapable of carrying oxygen. Bacteria and viruses can cause a number of illnesses such as typhoid fever, cholera, gastro-enteritis, hepatitis and meningitis.

Protection zones around planned boreholes are included to ensure there will be no effect on the groundwater quality as a result of on site sanitation.

The radius of a fracture as defined and calculated in the FC-spreadsheet (Van Tonder et al, 2001) can be used to determine the protection zone. Various protection zones can then be delineated with associated risks as shown in Table 8.2.

Table 8.2: Risk associated with various protection zones

Risk	**Protection zone**
High or very high risk of microbial pollution	2 times fracture radius

Low risk for microbial pollution	1 times fracture radius
No risk for microbial pollution	0.5 times fracture radius
High risk for N for infants	2 times fracture radius
Low risk for N for infants	1 times fracture radius
No risk for N for infants	0.5 times radius

In many cases fracture information is not available, therefore a correlation between fracture radii and transmissivity was determined:

$$Fracture_{radius} = 0.28T + 53$$

Transmissivity values can then be used to determine the fracture radii and protection zones.

Table 8.1: Methods for calculating the components of the water balance

Component	Definition	Method	References/software
Groundwater inflow (I) and outflow (O) across catchment boundaries	Areas along the boundary where groundwater enters or leaves the catchment. Usually the catchment boundary acts as a groundwater water divide, and it is only in low-lying areas that groundwater will enter or leave the system.	Groundwater levels in an aquifer usually (in more than 95% of aquifers studied in South Africa) follow surface topography. As a result, Bayesian interpolation techniques can be used, and a groundwater contour map can be plotted. After constructing the Bayesian groundwater level contour map, there are two methods that can be used to estimate *I* and *O*, namely numerical flow models and Darcy's Law.	Reference Darcy's Law can be obtained from Kruseman and De Ridder (1991). The transmissivity or hydraulic conductivity needed in the flow calculations can be obtained from literature (e.g. Kruseman and De Ridder, 1991) or pumping test data. Software TRIPOL (Van Tonder et al., 1996) can be used to perform the Bayesian interpolation. It is available on the IGS website: www.uovs.ac.za/igs PMWIN version 5 (Chiang and Kinzelbach, 1999), a numerical flow model, can be downloaded from the IGS website.
Groundwater abstraction	Withdrawing water from the aquifer, normally by means of a borehole	Databases, such as the National Groundwater Database (NGDB) and Water Resource Management System (WRMS), can be used. A hydrocensus would also give an indication of abstraction rates. If a useful database	For more information concerning databases, refer to the DW&EA website, www.DW&EA.gov.za.

Component	Definition	Method	References/software
		does not exist, information, such as land use maps (for estimating irrigation) and population maps (for estimating drinking and industrial uses) can be used to estimate the existing abstraction rates.	
Recharge	Recharge is defined as the process by which water is added from outside to the zone of saturation of an aquifer, either directly into a formation, or indirectly by way of another formation.	Chloride method, saturated volume fluctuation method, cumulative rainfall departure method, isotopes and maps. For more information concerning the most commonly used methods, refer to Appendix A.	Reference Bredenkamp et al. (1995) and Xu and Beekman (2003) discuss these methods in detail. Software An EXCEL-spreadsheet programme, RECHARGE (Van Tonder and Xu, 2000) can be used to determine the net groundwater recharge. Available from the IGS website, www.uovs.ac.za/igs. Maps Vegter's (1995) groundwater recharge map can be used.
Flow from surface water bodies	Surface water bodies can recharge or discharge groundwater. The exchange rate of water is usually controlled by the difference in	See groundwater inflow (I) and outflow (O) across catchment boundaries.	See groundwater inflow (I) and outflow (O) across catchment boundaries.

Component	Definition	Method	References/software
	hydraulic heads (water levels) and resistance of the media between the groundwater and surface water bodies.		
Basic human needs	The least amount of water required to satisfy basic water requirements; this is currently set at 25 ℓ/cap·d.	The amount of groundwater needed for basic human needs can be determined by multiplying the number of people dependent on groundwater by 25 ℓ/cap·d. Future changes in the groundwater-dependent population must also be considered.	Reference Water Services Act (Act No. 108 of 1997).
Ecological requirements	The amount of groundwater needed to sustain aquatic ecosystems.	In the case of a line source (e.g. river) determine groundwater component of baseflow using the Herold method. It is important to note that these values must be scaled according to the various reaches within a river. In the case of a point source (e.g. wetland) determine the groundwater flow towards the source by means of Darcy's law or a numerical flow model.	Reference Herold method (Vegter, 1995). Data needed to calculate baseflow can be obtained from WR90 (Midgley et al., 1994) or Hughes (2003) or field data. Software Base flow can be calculated using the reserve spreadsheet available from IGS website, www.uovs.ac.za/igs. For point sources, see flow across catchment boundaries.

9 Description of the software

The intended functionality of the software and the structure of the system are discussed in detail in the accompanying manual. It is largely adapted from Dennis (2007). The software is still based on the manual of Parsons and Wentzel (2007) and does not yet incorporate the latest developments in Classification and its impact on groundwater in particular as proposed in this treatise.

9.1 Introduction to the GRDM

GRDM comprises six sequential phases of investigation, including the core outputs of Classification, Reserve determination and setting Resource Quality Objectives. Because of groundwater's unique characteristics, methods of assessment are somewhat different from other components of the hydrological system (rivers, wetlands, estuaries), but it is crucial that Resource Directed Measures (RDM) assessments be undertaken in an integrated manner.

Four levels of GRDM assessment are recognised – desktop, rapid, intermediate, comprehensive – with each providing an increased level of confidence. Increased levels of commitment and resources are required to attain higher levels of confidence. Desktop GRDM assessments can be completed in a matter of hours, but comprehensive GRDM assessments may take over a year to complete. The same level of assessment need not be applied across a study area, and a multilevel GRDM assessments approach can be adopted. Rapid level assessments could suffice in low usage areas, in low stress areas or in instances where usage is expected to have limited impact. Assessments that are more detailed may be undertaken in areas where specific problems occur or in areas where the underlying groundwater system is clearly stressed.

It must be stressed that the methodology and by implication, the software, makes no distinction between the different level of assessment. The accuracy of the assessment is purely a function of the reliability of the software as well as the skills of the professional that is doing the assessment.

9.2 Overview of the Graphical User Interface

9.2.1 Layout of the Main Form

This section contains an introduction to the main form of the system. The GRDM is divided into two main areas namely:

Road Map – The purpose of the road map is to guide the user through the sequential steps that outlines the GRDM process. The road map is shown in Fig 9.1

Spatial Data – This section provides the user with a GIS interface. The GIS is used to delineate the area in question that correspond with step 3 in the GRDM process and collect information regarding the area from a set of supplied shape files and GRAII data. It is shown in Fig 9.2

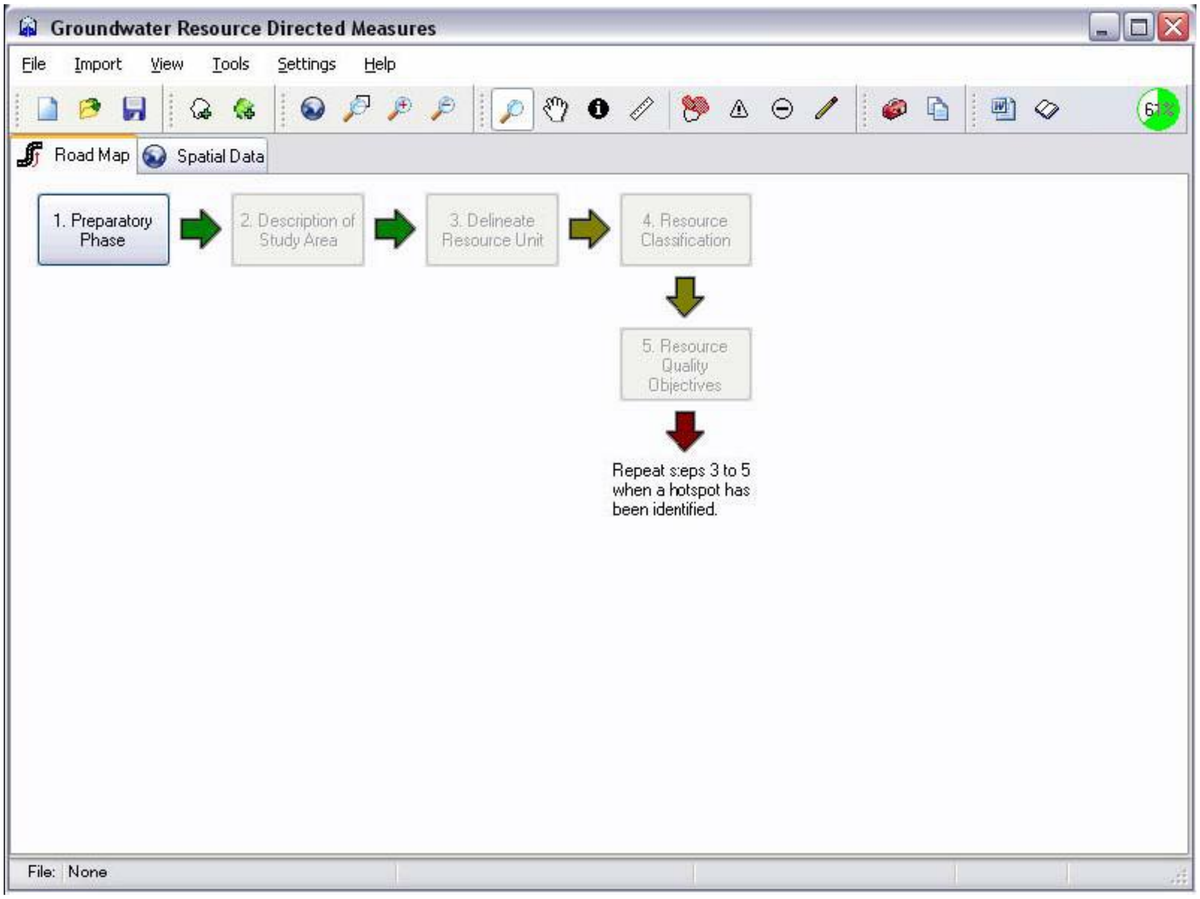


Figure 9.1 layout of the main form

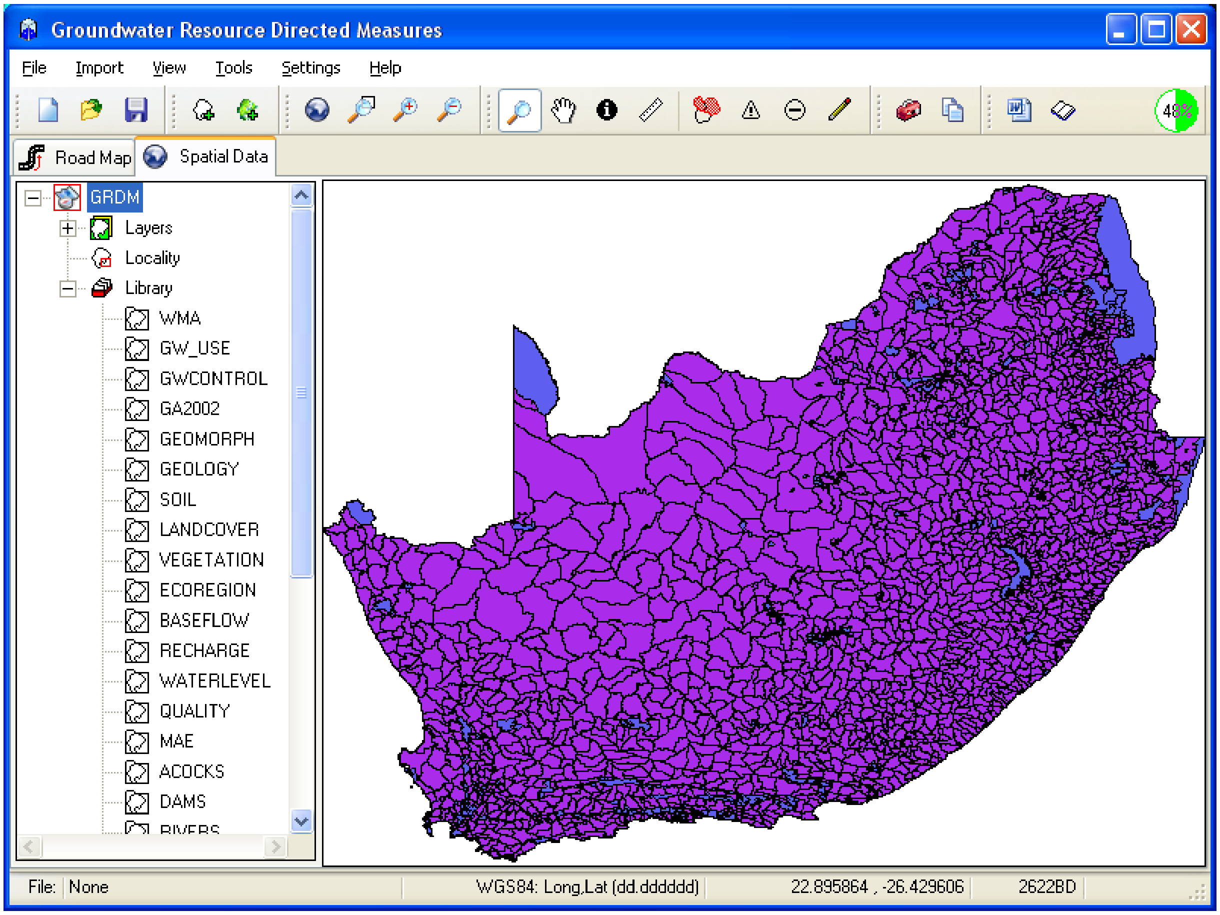


Figure 9.2 layout of the spatial data screen

A list of spatial datasets that are available in the GRDM software is listed in table 9.1

Layer	Attributes
Quaternary	Values derived from WR90 data
Protected areas	DW&EA Resource Assessment Phase 2 03

WMA	Department of Water and Environmental Affairs, Pretoria
Ground water use	CSIR - Simon Hughes Total groundwater use
GWCA	Department of Water and Environmental Affairs
NGDB	Static waterlevels (WL) and median waterlevel from time-series data (WLE) from NGDB data February 2005
gw REGIONS	Vegter groundwater regions
Chemist ry points	Chemistry points from NGDB selected for classification purposes
Catch SW interaction	WR90 catchments joined with parameters from Karim Sami
Catch water use	Recharge Percentage per WR90 catchment
E baseflow index	Groundwater contribution to baseflow index per quaternary catchment WRC_Parsons
Dams	Department of Water and Environmental Affairs
Acocks Veld Types	Botanical Research Institute
MAE	Mean annual evaporation WR90
Quality	Total dissolved solids Department of Water and Environmental Affairs
Waterle vel	Depth to groundwater level Department of Water and Environmental Affairs
Recharg e	Vegter 1995 Department of Water and Environmental Affairs, Pretoria
Baseflo w	Vegter 1995 Department of Water and Environmental Affairs

Ecoregion	Ecoregion level 1 Department of Water and Environmental Affairs
Vegetation	Low, A.B. and Rebelo, A.G. DEAT
Landcover	CSIR consortium
Soil	SURFACE WATER RESOURCES OF SOUTH AFRICA 1990: WR90 Water Research Commission
Geology	Council for Geoscience
Geomorphology	Department of Water and Environmental Affairs
GA 2002	Department of Water and Environmental Affairs
GW control areas	Department of Water and Environmental Affairs
Roads	Department of Water and Environmental Affairs

Table 9.1 List of datasets included in the GRDM software

The spatial datasets should be used by the professional to familiarise himself with the area and to obtain default values of most of the parameters required in the GRDM assessment. It is also possible to import raster and vector files of a particular area that is not available in the standard set.

This is mostly used in the step 3 where the resource is described in terms of the requirements of the GRDM process.

9.3 SYSTEM DESIGN

This section describes the methodology and the functionality captured in the GRDM.

9.3.1 Interface

The standard Windows type file menu is implemented on the main menu with the following tool buttons on the main toolbar under “File” as is shown in Fig 13.3:

	Create a new GRDM project.
	Open an existing GRDM project.
	Save the current GRDM project.

Figure 9.3. The main toolbar

The following document related tools are both available on the main menu and main toolbar (Fig 9.4):

	Generate a report.
	Load GRDM manual.
	Launch the groundwater dictionary.

Figure 9.4 Document related tools available on the main menu

Saved project files can be distributed amongst users without distributing the additional imported datasets e.g. shape files or georeferenced images, since the GRDM embeds all imported data in the project file.

The GRDM interface makes use of the legend in Fig 13.5 to assist the user in completing the various field values:

	Required field	These fields are compulsory and must be completed before the application will allow the user to continue along the road map.
	Calculated field	These fields are calculated by using the supplied data on the same dialog.
	Map value	Clicking this button will fetch the map value for the selected area.
	Toolbox value	Clicking this button will fetch the last value calculated using the toolbox for the specific field.

Figure 9.5 Legend that explains the meaning of various field values

9.3.2 Road Map

The road map guides the user through the GRDM process as outlined in the phases that follow. More detail regarding the different phases is available in the GRDM manual that accompanies the software. The GRDM manual file is available under the Docs directory as shown in Figure 9.4.

STEP 1 - Preparatory Phase

The preparatory phase collects information about the assessor, the level of assessment and the following general information:

Impact of the license

Current use

Special features

Strategic purpose

The input screen of this phase is shown in Figure 9.6

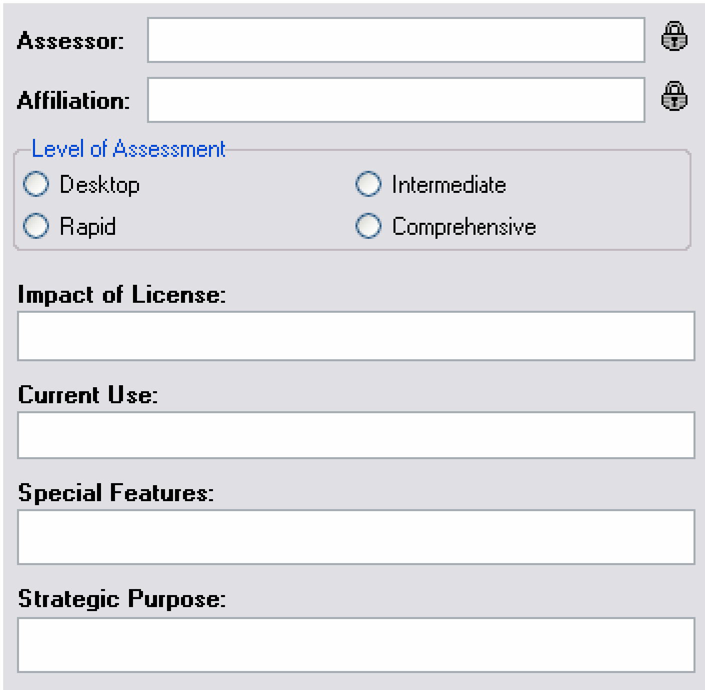


Figure 9.6 Input screen for the prepatory phase

STEP 2 - Description of Study Area

The description of the study area requires the name of resource unit in question together with the following area specific information:

Resource unit description

Introduction

Background

Physiography and climate

Geohydrology

The input screen of this phase is shown in Figure 9.7

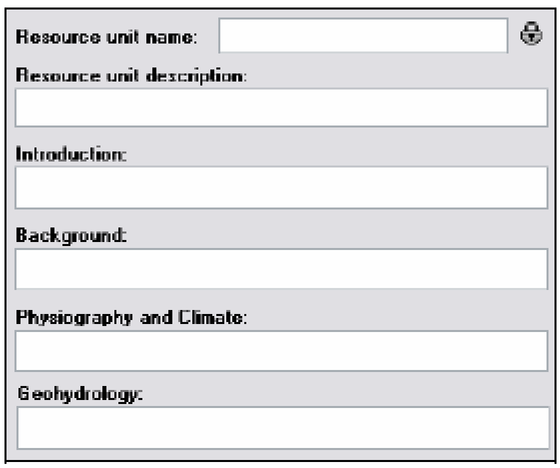


Figure 9.7 Input screen for the prepatory phase

STEP 3 - Delineate Resource Unit

Delineation of the resource unit requires interaction with the Spatial Data interface which is described in section 3.3 and a delineation motivation. The input screen of this phase is shown in Figure 9.8.

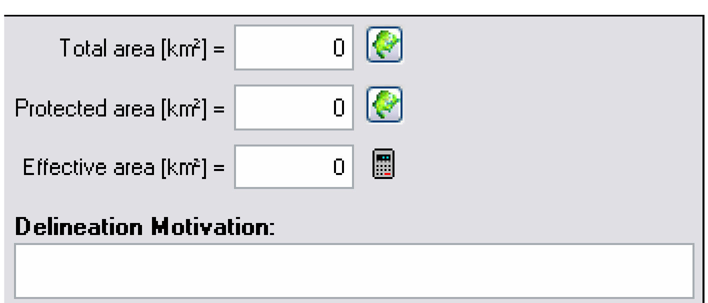


Figure 9.8 Delineation of resource unit input dialog

Once the delineation has been completed in the Spatial Data interface the user can click on to automatically calculate the resource unit area as well as the protected area if any exists.

The dialog presenting the quantification of the reserve also appears after the delineation has taken place as shown in Figure 9.9. The inputs of this dialog should be completed by the user using map values, toolbox values or user supplied values. All outputs are calculated using the input values and are indicated with

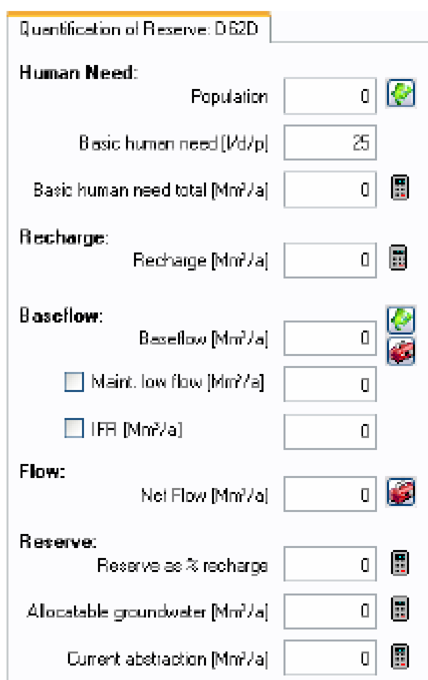


Figure 9.9 Quantification of the Reserve

STEP 4 - Resource Classification

The resource classification requires the abstraction and the recharge to calculate the reserve quantity category as shown in Figure 9.10. The user must also set the appropriate present status category and vulnerability.

Typical examples of the various impact ratings are given at the bottom of the dialog to assist the user in rating the expected impact under the vulnerability section.

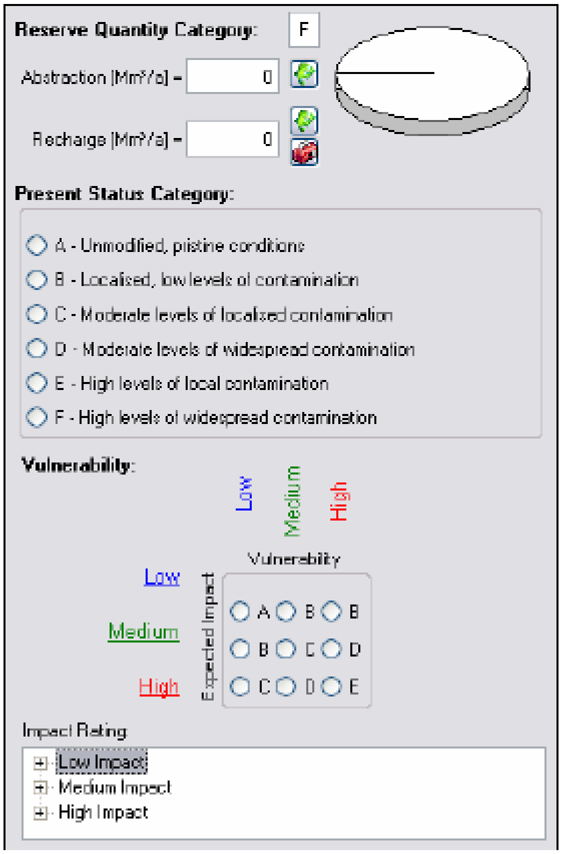


Figure 9.10 - Resource classification input dialog

STEP 5 - Resource Quality Objectives

The resource quality objectives require the user to make selections regarding the following categories:

- Rivers
- Groundwater Use
- Springs
- Wetlands / Estuaries
- Protected Area
- Geology

Once the selections have been made the user can click on Generate Guidelines to specify the RQO together with a list of suggested tools to use. The input screen of this phase is shown in Figure 9.11.

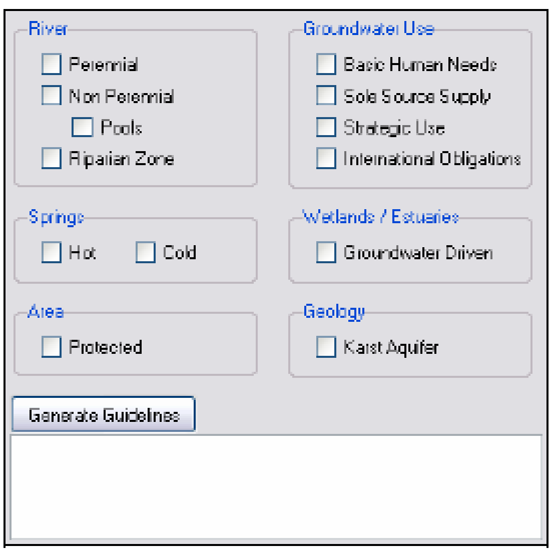


Figure9.11- Resource quality objectives input dialog

10 References

Adam, P. (1994) Saltmarsh and mangrove. In *Australian Vegetation*, 2nd Edition, ed. R.H. Groves, 395-435. Cambridge Univ. Press.

Baron, J., Seward, P. and Seymour, A. (1998). *The groundwater harvest potential map of the Republic of South Africa.* Technical report Gh 3917. Directorate of Geohydrology, Department of Water and Environmental Affairs, Pretoria.

Bouwer, H. (1978). *Groundwater Hydrology*. McGraw-Hill, Tokyo.

Braune, E. (2000). *Groundwater management in terms of the National Water Act, 1998.* In: Course on Groundwater and the National Water and Water Services Act, Pretoria.

Bredehoeft, J. (1997). Safe yield and the water budget myth, *Ground Water*, **35** (6) 929.

Bredenkamp, D.B., Janse Van Rensburg, H., Van Tonder, G.J. and Botha, L. J. (1995). *Manual on quantitative estimation on groundwater recharge and aquifer storativity*. Report TT 73/95. Water Research Commission, Pretoria.

Brown, C., Colvin, C., Hartnady, C., Hay, R., Le Maitre, D. and Rieman, K. (2003). *Ecological and environmental impacts of large-scale groundwater development in the Table Mountain Group.* Draft discussion document. Water Research Commission, Pretoria.

Campbell, E.E. and Bate, G.C. (1998). Tide-induced pulsing of nutrient discharge from an unconfined aquifer into an *Anaulus australis*-dominated surf-zone, *Water SA* 24 (4) 365-370.

Chiang, W.H. and Kinzelbach, W. (1999). *Processing Modflow (PMWIN) – a simulation system for groundwater flow and transport modelling*. Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Cleaver, G., Brown, L.R., Bredenkamp, G.J. and Smart, M.C. (2003). Assessment of environmental impacts of groundwater abstraction from Table Mountain Group (TMG) aquifers on ecosystems in the Kammanassie Nature Reserve and environs. Draft WRC report K5/1115 in preparation.

Colvin, C., Le Maitre, D. and Hughes, S. (2003). *Assessing terrestrial groundwater dependent ecosystems in South Africa.* WRC Report 1090-2/2/03. Water Research Commission, Pretoria.

Colvin, C. (2003). Guidelines on setting resource quality objectives for groundwater. Project no. K1235 progress report.

Colvin, C., Cave, L. and Saayman, I. (2004). *A functional approach to setting Resource Quality Objectives for Groundwater*. WRC Project No. K1235. Water Research Commission, Pretoria.

Colvin, C., Le Maitre, D., Saayman, I. and Hughes, S. (2005). *An Introduction to Aquifer Dependant Ecosystems in South Africa.* WRC Project K5/1330. Water Research Commission, Pretoria.

Colvin, C. (2005). *GRDM Manual. Prepared for DW&EA as part of the Groundwater Resource Assessment* Phase II Project.

Conrad, J., Low, A.B., Munch, Z. and Pond, U. (2005). *Remote sensing based botany and groundwater dependency study: Northern Sandveld*. Report submitted to Department of Water and Environmental Affairs. Report number RDM/G300/02/CON/0505. Submitted by GEOSS (Pty) Ltd and Coastec.

Conrad, J. and Van Der Voort, I. (1998). An investigation into a GIS based methodology to determine the sustainable exploitability of South African aquifers. WRC Report No. 840/1/98. Water Research Commission, Pretoria.

Cook, P.G. and Herczeg, A.L. (1998), *Groundwater chemical methods for recharge studies*. Part 2. The basics of recharge and discharge. CSIRO Australia

Constitution of the Republic of South Africa (Act No. 108 of 1996).

CSIR-IZNA. (2002). *Integrated Water Resource Management: Guidelines for Groundwater Management in Water Management Areas, South Africa.* Editor: C. Colvin, Groundwater Project Leader: CSIR-IZNA Consortium, Stellenbosch, South Africa.

Danielopol, D.L. (1989). Groundwater fauna associated with riverine aquifers. *J. N. Am. Benthol. Soc*. 8,18-35.

Danielpol,D. L.,Griebler. A., Gunatilaka and Noteboom, J. (2003). *Present state and future prospects for groundwater ecosystems.* Environmental Conservation 30: 104-130

Dennis, I., Van Tonder, G.J. and Rieman, K. (2002). *Risk based decision tool for managing and protecting groundwater resources.* WRC Report 969/1/02. Water Research Commission, Pretoria.

Dennis, R. (2007). *Software design document: Groundwater Resource Directed Measures*: Phase 1, Activity 34. Project number: 14/14/2/3/8/1 Report prepared for DW&EA.

Driscoll, F.G. (1995). *Groundwater and Wells*. US Filter Johnson Screens, St Paul MN.

DW&EA (Department of Water and Environmental Affairs) (1999a). *Resource Directed Measures for protection of water resources* – Volume 1: Integration Manual; Version 1.0, Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (1999b). *Resource directed measures for protection of water resources.* Volume 2: Integrated manual, Version 1.0. Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (1999c). *Resource directed measures for protection of water resources* – Volume 6: Groundwater component, Version 1.0. Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (1999d). *Water resources protection policy implementation – resource directed measures for the protection of water resources,* Volumes 2–6, Version 1.0. Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (2000). *Policy and strategy for groundwater quality management in South Africa*. No. W.1.0: First edition. Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (2002a). *National Water Resource Strategy*. Proposed first edition, August 2002, Department of Water and Environmental Affairs, Pretoria.

DW&EA (Department of Water and Environmental Affairs) (2002b). *Methods for assessing water quality in ecological reserve determinations for rivers*, Version 2, Draft 15.0. Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2003). Development of resource directed water quality management policies: draft guideline for determining stress, setting of resource quality objectives and the allocatable resource. Water Resource Planning Systems, Sub-series No. WQP 1.4.3.1, Version 1.0, Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2003) Water resource planning systems. Sub Series No. WQP 1.5. Resource Directed Water Quality Management Policy. Version 1.0. Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2003). *Resource Directed Measures* – Module 1 – Introductory module. October 2003 edition. Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2004). *Guide to the National Water Act.* Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2004). *National Water Resource Strategy.* First edition. Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2005). *A Toolkit for water allocation reform.* Department of Water and Environmental Affairs, Pretoria.

DW&EA(Department of Water and Environmental Affairs) (2007). *Guidelines for Catchment Management Strategies*. First edition.

Freeze, R.A. and Cherry, J.A. (1979). *Groundwater*, ISBN 0-13-365312-9, Prentice-Hall, Inc.

Gardner, K.M. (1999). *The importance of surface water/groundwater interactions*. Issue paper. Environmental Protection Agency, Seattle.

Gieske, A. (1992). Dynamics of groundwater recharge – a case study in semi-arid eastern Botswana. PhD thesis, Vrije University, Amsterdam.

Gilbert, J. (1996). *Do groundwater ecosystems really matter*? In Groundwater and Land-Use Planning Conference Proceedings (Eds. C. Barber and G. Davis), pp. 1-.Centre for Groundwater Studies, CSIRO Division of Water Resources, Perth.

Giljam, R. (2003). *The effect of the Cape Flats Aquifer on the water quality of False Bay*. MSc. Thesis (unpublished), University of Cape Town, Cape Town, South Africa.

Hatton, T. and Evans, R. (1998). *Dependence of ecosystems on groundwater and its significance to Australia.* Occasional paper no. 12/98. Land and Water Resources Research and Development Corporation, CSIRO, Australia.

Herold, C. (1980). *A model to compute a monthly basis diffuse salt loads associated with runoff*. HRU Report No. 1/80. Rhodes University, Grahamstown, South Africa.

Hughes, D.A. and Munster, 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, Grahamstown, South Africa.

Hughes, D.A, (2003). Incorporating ground water recharge and discharge functions into an existing monthly rainfall-runoff model. In press.

Hughes, D.A. (2003). *RESDSS*. Institute for Water Research, Rhodes University, Grahamstown, South Africa.

Kirchner, J., Van Tonder, G.J. and Lucas, E. (1991). *Exploitation potential of Karoo aquifers*. WRC Report 170/1/91. Water Research Commission, Pretoria.

Kleynhans, C.J. and Hill, L. (1998). *A preliminary ecoregion classification system for South Africa. Internal report*. Institute for Water Quality Studies, Department of Water and Environmental Affairs, Pretoria.

Kok, T.S. (1992). *Recharge of springs in South Africa*. Unpublished Technical Report Gh 3748. Directorate of Geohydrology, Department of Water and Environmental Affairs, Pretoria.

Kruseman, G.P. and De Ridder, N.A. (1990). *Analysis and evaluation of pumping test data.* Publication No. 47. Second Edition. International Institute for Land Reclamation and Improvement, Wageningen, The Netherlands.

Lerner, D. (1999). *Surface–groundwater interactions in the context of groundwater resources.* Paper presented at workshop on Surface–groundwater Issues in Arid and Semi-arid Areas, Warmbaths, South Africa.

Longley, G. (1992). *The subterranean aquatic ecosystem of the Balcones Fault Zone Edwards Aquifer in Texas threats from overpumping*. 291-300 *In* Stanford, J.A. and Simons (eds). Proceedings of the First International Conference on Groundwater Ecology. American Water Resources Association, Bethesda, Maryland, United States of America.

Midgley, D.C., Pitman, W.V. and Middleton, B.J. (1994). *The surface water resources of South Africa 1990*, Volumes 1-6. Report No 298/1/94. Water Research Commission, Pretoria.

Murray, E.C. (1996). *Guidelines for assessing single borehole yields in secondary aquifers.* MSc. Thesis (unpublished), Rhodes University, Grahamstown, South Africa.

National Water Act (Act No. 36 of 1998).

O'keefe, V., Gates, G. and Kalaitzis, P. (1998). *Developing groundwater policy for sustainable groundwater management in NSW, Australia*. IAH International Conference Proceedings, Melbourne, Australia. February 1998, 857-862.

Papini, G., Parsons, R.P., Rosewarne, P., Woodford, A. and Beuster, H. (2001). *A hydrocensus of groundwater use in the Hex River Valley*. Report submitted to the Department of Water and Environmental Affairs and the Hex Valley Irrigation Board.

Parsons, R.P. (1994). A review of approaches and methodologies for determining leachate generation at waste disposal sites and groundwater recharge. WRC Report No. 564/1/94. Water Research Commission, Pretoria.

Parsons, R.P. (1995). *A South African aquifer system management classification*. WRC Report No. 77/95. Water Research Commission, Pretoria.

Parsons, R.P. (2002). *Recharge of the Table Mountain Group aquifer systems;* in Pietersen, K. and Parsons, R.P. (eds) A synthesis of the hydrogeology of the Table Mountain Group - Formation of a research strategy. Report No. TT 158/01. Water Research Commission, Pretoria, 97-102.

Parsons, R.P. (2003). Thukela water decision support phase: Reserve determination phase – groundwater scoping report. Report PBV000-00-10304. Parsons and Associates, Somerset West.

Parsons, R.P. (2003). Surface water – groundwater interaction in a Southern African context – a geohydrological perspective. WRC report TT218/03. Water Research Commission, Pretoria.

Parsons, R.P. and Conrad, J.E., (1998). *Explanatory notes for the aquifer classification map of South Africa*. WRC Report No. 116/98. Water Research Commission, Pretoria.

Parsons, R.P. and Wentzel, J. (2007). *GRDM Training Manual*. WRC Project 1427, Water Research Commission, Pretoria.

Petts, G.E., Bickerton, M.A., Crawford, C., Lerner, D.N. and Evans, D. (1999). *Flow management to sustain groundwater-dominated stream ecosystems, Hydrological Processes,* **13** 497-513.

Ramsar Conference of the Parties (2005) Wetlands and water: supporting life, sustaining livelihoods. Kampala, Uganda, 8-15 November 2005

Sami, K. (2003). A comparison of recharge estimates in a Karoo aquifer from a chloride mass balance in groundwater and an integrated surface – subsurface model; in Xu, Y. and Beekman, H.E. (eds) (2003) Groundwater recharge estimation in Southern Africa. UNESCO IHP Series No. 64. UNESCO, Cape Town.

Sanders, T.G., Ward, R.C., Loftis, J.C., Steele, T.D., Adrian, D.D. and Yevjevich, V. (2000). *Design of Networks for Monitoring Water Quality*. 4th Printing. Water Resources Publications, LLC. Colorado, United States of America.

Schulze, R.E. (1997). *South African atlas of agrohydrology and climatology*. Technical Report TT82/96. Water Research Commission, Pretoria.

Scott, D.F. and Le Maitre, D.C. (1997). *The interaction between vegetation and groundwater – research priorities for South Africa*. WRC Project K5/730. Water Research Commission, Pretoria.

Sinclair Knight Merz Pty. Ltd. (2001). *Environmental water requirements of groundwater dependent ecosystems* Technical Report No 2 Environment , ISBN 0 642547696, Canberra, Australia.

Smaktin, 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.

Smaktin, V.U. and Watkins, D.A. (1997). *Low flow estimation in South Africa*. WRC report 494/1/97. Water Research Commission, Pretoria.

Smart, M.C. (1998). *Regional hydrogeological mapping – Queenstown, South Africa.* IAH International Conference Proceedings, Melbourne, February 1998, 739-744.

Tasaki, S. (2003). WRC sponsored MSc research project in progress, University of Johannesburg, Johannesburg, South Africa.

Tharme, R.E. (1996). *Review of international methodologies for the quantification of the instream flow requirements of Rivers*. Report prepared for DW&EA by the Freshwater Research Unit, University of Cape Town, Cape Town, South Africa.

Tharme, R.E. and King,J.M. (1998). Development of the building block methodology for instream flow assessments and supporting research on the effects of different magnitude flows on riverine ecosystems. WRC Report 576/1/98. Water Research Commission, Pretoria.

Thornthwaite, C.W. and Mather, J.W. (1955). *The water balance.* Publ. Climatol. Lab. Climatol. Drexel Institute of Technology **8** (1) 1-104.

Todd, D.K., Tinlin, R.M., Schmidt, K.D., and Everett, L.G., (1976). *Monitoring groundwater quality: Monitoring methodology.* Report No. GE75TMP-68 prepared for the U.S. EPA by GEC.

Toth, J. (1999). Groundwater as a geological agent – an overview of the causes, process, and manifestations, *Hydrogeology Journal*, **7** 1-14.

Townley, L.R., Turner, J.V., Barr, A.D,, Trefry, M.G., Wright, K. D., Gailitis, V., Harris, and Johnston, C.D. (1993). *Wetlands of the Swan Coastal Plain*, Volume 3:–

Interaction between lakes, wetlands and unconfined aquifers. Water Authority of Western Australia, Perth, Australia.

Van Tonder, G.J. and Xu, Y. (2000). *RECHARGE - an EXCEL program to estimate recharge*. Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa.

Van Tonder, G.J., Kunstmann, H. and Xu, Y. (2001). *Flow characterization method (FC) software*. Version 3. Institute for Groundwater Studies, University of the Free State, Bloemfontein, South Africa.

Vegter, J.R. (1995). *An explanation of a set of national groundwater maps.* WRC report TT 74/95. Water Research Commission, Pretoria.

Vegter, J.R. (2001). Groundwater development in South Africa and an introduction to the hydrogeology of groundwater regions. WRC Report TT 134/00. Water Research Commission, Pretoria.

Vegter, J.R. and Pitman, W.V. (1997). *Recharge and streams flow*. Paper presented at workshop on groundwater–surface water issues in arid and semi-arid areas, 1-20.South Africa.

Water Services Act (Act No. 108 of 1997).

Winter, T.C., Harvey, J. W., Franke, O.L. and Alley, W.M. (1999). *Ground water and surface water – a single resource*. USGS Circular 1139. United States Geological Survey, Denver, United States of America.

Xu, Y. and Beekman, H.E. (eds) (2003). *Groundwater recharge estimation in Southern Africa*. UNESCO IHP Series No. 64. UNESCO, Cape Town.

Xu, Y., Colvin, C., Van Tonder, G.J., Le Maitre, D., Zhang, J. and Braune, E. (2002). *Determination of the Resource Directed Measures: Groundwater Component* (Version 1.1) WRC Programme K5/1090 – 1092

Xu, Y., Colvin, C., Van Tonder, G.J., Hughes, S., Le Maitre, D., Zhang, J., Mafanya, T., and Braune, E., (2003). *Towards the resource directed measures: Groundwater component.* WRC Report No. 1090-2/1/03. Water Research Commission, Pretoria