An Introduction to Aquifer Dependent Ecosystems in South Africa

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TT 301/07

Water Research
Commission

Aquifer Dependent Ecosystems in Key Hydrogeological Typesettings in South Africa

Christine Colvin, David le Maitre, Irene Saayman,
and Simon Hughes

Report to the
Water Research Commission

by

Natural Resources and the Environment
CSIR

WRC Report No TT 301/07
July 2007

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Obtainable from

Water Research Commission
Private Bag X03
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0031

This publication of this report emanates from a project entitled *Aquifer Dependent Ecosystems in Key Hydrogeological Typesettings in South Africa* (WRC project K5/1330).

Appendices appear separately on a CD which is inserted at the back of this report. See page viii for the list.

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ISBN 978-1-77005-531-5
Printed in the Republic of South Africa

EXECUTIVE SUMMARY

This report: *An Introduction to Aquifer Dependent Ecosysyems in South Africa* (WRC report number TT 301/07), has been published as the outcome of the Water Research Commission (WRC) project K5/1330, titled: *Groundwater-Dependent Ecosystems in Key Hydrogeological Settings in South Africa.* The report also includes ten appendices provided on a CD, issued with the report.

Aquifer Dependent Ecosystems (ADEs) occur throughout the South African landscape in areas where aquifer flows and discharge influence ecological patterns and processes. They are ecosystems which require groundwater from aquifers for all or part of their life-cycle, to maintain a habitat with a water budget, or water quality that contrasts with the surrounding ecosystems.

The multiplicity of types and scales of ADEs can be simplified into type-settings based on 8 principal aquifer types (based on lithology) and 7 habitat types. These type-settings describe the supporting aquifer type and ecosystem or habitat setting. Examples of known South African ADEs include:

- in-aquifer ecosystems in the dolomites (North West Province);
- springs and seeps in the TMG sandstone (Western Cape);
- terrestrial keystone species such as *Acacia erioloba* in the Kalahari;
- lakes and punctuated estuaries on the shallow sand aquifers of the east coast in KwaZulu-Natal; riparian zones in the seasonal alluvial systems of the Limpopo;
- seeps on the Karoo dolerite sills.

The identification of ADEs is often difficult but needs to be focused initially at a catchment scale, which is most relevant for water management and allocation. Proving links between ADEs and aquifers often requires detailed, multi-disciplinary observation and assessment. At a coarse national scale we can identify areas with a high probability of supporting terrestrial and aquatic ADEs. We can also assess aquifer vulnerability to disturbance of discharge regimes and potential hazards to ADEs to give a national scale ADE risk map. Both ADE occurrence and risk should be verified at a local scale, but the overview guides preliminary decision making about ecosystem protection and groundwater potential for abstraction.

South Africa is moving towards Integrated Water Resource Management (IWRM), enabled by new legislation and a transforming water sector. ADEs are beginning to be considered in the context of IWRM and provide an ecological boundary for sustainable groundwater use. Legislation exists within National Environmental Management Act (NEMA) and the National Water Act (NWA) to protect ADEs. A proposal to impact or develop a groundwater water resource should be subject to three tests: whether it impacts the requirements of the ecological Reserve, whether it impacts the Resource Quality Objectives (RQOs), and whether environmental standards and goals under NEMA are affected. These measures should safeguard the conservation and ecological requirements of ADEs, if fully implemented.

Successful protection of ADEs will require cooperative governance of land, water and the environment. The main custodians are the Department of Environment Affairs & Tourism (DEAT) and the Department of Water Affairs & Forestry (DWAF), but management needs to happen at the grass-roots level of farmers, mines and municipalities who manage aquifers on a day-to-day basis. It will be important to raise the public's awareness of the role aquifers play in sustaining the surface environment.

The four objectives of this project are listed in italics below and the results of the project summarised.

1. *To produce at a national scale a summary of known and probable groundwater dependent ecosystems in South Africa, based on hydrogeological-type settings.*

A typology for different aquifer dependent ecosystems has been defined, based on aquifer discharge types and ecosystem habitat types. Six main aquifer types have been categorised at a national scale, based on the primary lithology at a 1:1 million scale. These are Fractured Metasedimentary; Carbonates; Unconsolidated sediments; Dolerite dykes and sills; Basement complexes and younger granites; and Igneous extrusive. These categories group broadly similar hydrogeological characteristics that control aquifer discharge regimes linked to ecosystems. The different habitat types of the main kinds of Aquifer Dependent Ecosystems (ADEs) were also grouped in terms of terrestrial; aquatic; spring; riparian; wetland/ seep; estuarine; coastal and in-aquifer. Table 2.1 summarises the typology and gives the probability of occurrence of the different ADEs in South Africa. Figure 3.5 presents a national scale indication of key terrestrial and aquatic ADEs.

2. *To guide CMAs and DWAF in assessing the importance and vulnerability of groundwater dependent ecosystems within each type setting.*

Section 3 of the report describes the different type-settings and gives examples of ADEs within each. Typical ADEs with high biodiversity or ecological importance, e.g. riparian corridors in semi-arid areas, are introduced.

Sections 4 and 5 of the report introduce legislation which is relevant to protect ADEs (including the National Water Act (NWA) and the National Environmental Management Act (NEMA) and approaches to prioritising areas where ADEs are at risk. Current guidelines on the inclusion of groundwater in Environmental Impact Assessments (EIAs) make reference to aquifer linked ecosystems. Implementation of the Resource Directed Measures under the NWA will enable catchment managers to protect ADEs in the future. However, it is intended that the degree of protection will be differentiated depending on the Class given to the water resource. An approach demonstrated at a national scale indicates the vulnerability of ADEs, hazards and a combined risk assessment. High areas of risk are linked to shallow discharge zones where over abstraction is taking place and mining and irrigated agriculture dominate land-use.

3. *To test the application of the tools identified for measuring groundwater use and dependency. This is expected to include work in ephemeral alluvial settings and hypogean karst habitats.*

Appendices G and H describe two study sites established as part of this project. One site is at the Langebaan lagoon where an aquifer discharge zone is believed to be linked to an intertidal wetlands area of high ecological importance. This coastal sand type-setting has been investigated using geophysics, drilling, hydrogeochemical and water level measurements. A further WRC project, lead by UCT, is investigating in more detail the hydrogeochemical influence of the aquifer on the rooting zone of the wetland.

Another site investigates riparian and terrestrial type-settings in the northern Kruger Park. Here geophysics, drilling, water level measurements, hydrogeochemistry and plant water isotopes have been used to assess the dependency of trees on groundwater in aquifers and aquitards. A monitoring network of six dedicated boreholes has been established and research is on-going in collaboration with SanParks.

4. *To identify significant knowledge gaps and to recommend a strategy for further research to address key issue relating to groundwater dependent ecosystems.*

Recommendations for further research are given in Appendix F. In summary, research projects and sustainable management should focus on:

- monitoring field data is required for groundwater levels and the determination of aquifer discharge areas;
- specific investigations on the nature of the aquifer – ecosystem interface are required to refine our understanding of dependency;
- broader ecological and economic assessments of ADEs will be needed to inform the level of protection required and acceptable levels of risk in managing the groundwater requirements for these systems.

Specific recommendations are given for the knowledge gaps on the role of aquifers in the different habitat types.

In addition to meeting the overall objectives of the project, the project team sourced co-funding and support from DWAF and South African National Parks, to establish long-term groundwater monitoring sites linked to aquifer discharge zones and ecological use. The monitoring of these areas is now carried out by CSIR and SANParks and the data are linked to DWAF's National Groundwater Archive.

Capacity building has been achieved through three different mechanisms within the project. Firstly in terms of formal academic education, a student from the University of Venda, F. Ramusiya, has completed his M.Sc characterising the hydrogeology of one of the field sites at Shingwedzi in the Kruger Park. The project has also contributed significantly to the Ph.D studies of the project leader, C. Colvin. Secondly, three workshops were carried out as part of this project to discuss the issue of aquifer dependency with a broad group of ecological experts and catchment managers, developing capacity and awareness in this group. Thirdly, conservation managers at the field sites have been trained in groundwater monitoring and introduced to the concept of ADEs

ACKNOWLEDGEMENTS

The authors wish to acknowledge the active support of the Department of Water Affairs, who provided drilling support for field investigations as part of this project, in particular Mr E van Wyk, Mr C Deysel and Ms M Nel. Also from the Department of Water Affairs, data from the Groundwater Resource Assessment (GRA) project was made available, and we acknowledge the support of Mr J Girman and Mr E Braune.

Field work as part of this project has been supported by SanParks, and Dr H Biggs, Mr P Nel and Ms A Gaylard are gratefully acknowledged,

We thank the steering committee and participants of regional workshops for their valuable advice and contributions.

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ABBREVIATIONS

ADEs	Aquifer Dependent Ecosystems
CMA	Catchment Management Agency
DEAT	Department of Environment Affairs and Tourism
DWAF	Department of Water Affairs and Forestry
EIA	Environmental Impact Assessments
EMP	Environmental Management Policy
GDEs	Groundwater Dependent Ecosystem
GRA	Groundwater Resource Assessment
GRDM	Groundwater Resource Directed Measures
IWRM	Integrated Water Resources Management
Mbgl	Metres below ground level
NBA	National Biodiversity Act
NEMA	National Environmental Management Act
NGA	National Groundwater Archive
NWA	National Water Act
RDM	Resource Directed Measures
RQOs	Resource Quality Objectives
SANBI	South African National Biodiversity Institute
WRC	Water Research Commission

1. INTRODUCTION

This book introduces the reader to aquifer dependent ecosystems (ADEs) in South Africa. It aims to raise awareness of the critical links between aquifers and the surface environment so that environmental requirements for groundwater can be protected. The importance of ADEs as keystone ecosystems and highly productive ecotones is presented.

This book describes typical ADEs, linking aquifer discharge regimes to habitats in type-settings. Aquifer discharge is controlled by climate and the rock type of the aquifer, and the latter has been simplified into 6 main types of aquifers found in South Africa. The typical habitats associated with aquifer discharge are terrestrial aquifers, wetlands, seeps, springs, in-aquifer ecosystems, riverine aquatic ecosystems, riparian zones, estuaries and the coastal zone. Only springs and in-aquifer ecosystems are exclusively aquifer dependent. All the other habitats may rely on surface water, soil moisture or direct rainfall, and often distinguishing those which are aquifer dependent is not easy.

Aquifer dependent ecosystems occur at a variety of scales within the landscape. A spring may be only a metre or two in extent, whereas plants may root down to shallow water tables across an area of many square kilometres. This handbook provides an overview of the probability of occurrence of ADEs at a national scale using data sets on vegetation and calculated baseflow which provide the best available indication. These do not locate specific ADEs, particularly springs and wetlands at the smaller scale, but indicate broad areas where they can be expected.

The management of ADEs presents a challenge to catchment managers and scientists alike, and successful protection will be a measure of the ability to achieve sustainable management in an integrated way. This book introduces some of the legal mechanisms which should be implemented to protect groundwater requirements for ecosystems and ensure the sustainable management of aquifers.

The accompanying report on this WRC project includes two appendices giving more detail on groundwater–surface water interactions (Appendix A) and groundwater links to terrestrial vegetation (Appendix B). The reader may wish to follow up some of the literature cited here or in the extended reference list (Appendix I) to investigate a particular ADE in more depth.

ADEs cross the boundary between the study of the physical earth systems and hydrogeology, and the study of biological ecosystems and ecology. Catchment managers and investigating scientists from all disciplines are faced with a wide range of terminology in the ADE debate. A selection of relevant terminology is presented in the glossary with accepted referenced definitions.

1.1 WHO SHOULD READ THIS BOOK

This book is intended for catchment managers, groundwater managers and users and students of integrated water resource management (IWRM). Groundwater abstraction is managed by bulk water suppliers, mining houses, farmers and other individuals. All of these groundwater managers can have a significant impact on ADEs. It will also be of interest to those involved in protecting the natural environment, ensuring sustainable use of water resources and maintaining biodiversity, as well as students of hydrogeology, ecology and eco-hydrology.

1.2 OTHER IMPORTANT SOURCES OF INFORMATION

This handbook is accompanied by a poster *Aquifer Dependent Ecosystems in South Africa. (See accompanying CD)*

The Department of Water Affairs and Forestry (DWAF) has published guidelines on setting a groundwater Reserve for aquatic ecosystems – the Groundwater Resource Directed Measures Manual, 2004. This can be obtained from the Resource Directed Measures (RDM) Directorate at DWAF.

The Water Research Commission (WRC) has published several reports which complement this introduction. The reader is referred to their website www.wrc.org.za and specifically to *Determination of the Resource Directed Measures: Groundwater Component*, 2002, Xu et al.; *Assessing Terrestrial Groundwater Dependent Ecosystems in South Africa*, 2002, Colvin et al.; and *Surface Water – Groundwater Interaction in a South African Context*, 2003, Parsons.

It is assumed that the reader has a basic knowledge of ecology and hydrogeology. Introductory texts are available on the internet and free from the WRC.

2. INTRODUCTION TO AQUIFER DEPENDENT ECOSYSTEMS

2.1 WHAT ARE AQUIFER DEPENDENT ECOSYSTEMS?

Aquifer dependent ecosystems are ecosystems which depend on groundwater in, or discharging from, an aquifer. They are distinctive because of their connection to the aquifer and would be fundamentally altered in terms of their structure and functions if groundwater was no longer available.

When hydrogeologists talk about groundwater they specifically mean the water that occurs in saturated aquifers or aquitards. Other scientists, such as ecologists or plant physiologists, may incorrectly refer to all underground water as groundwater, including interflow or soil water. Figure 2.1 below illustrates different components of the hydrological cycle and the terminology used to describe them. The glossary gives full definitions of the different components of the water cycle.

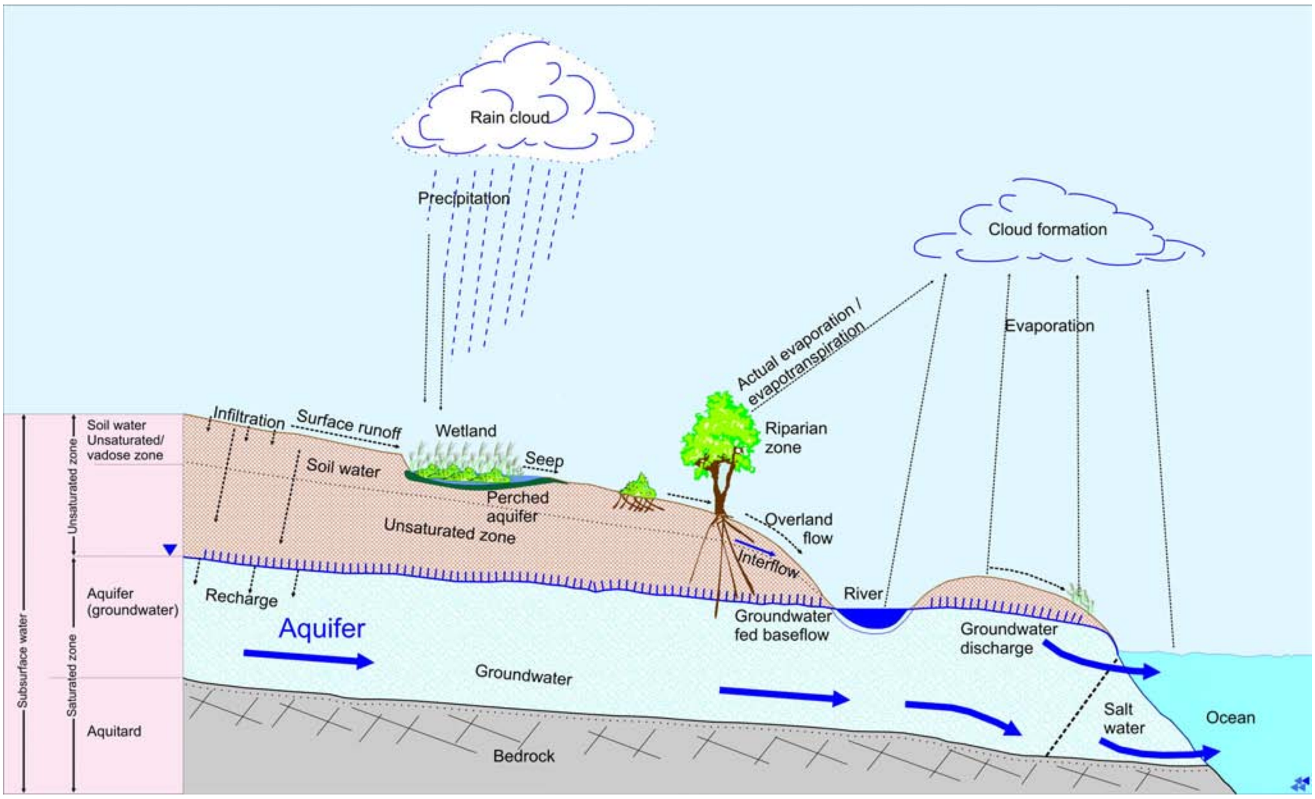


Figure 2.1: Subsurface and surface flows of water in the environment.

South African water legislation does not define the term groundwater but defines aquifers as "A geological formation which has structures or textures that hold water or permit appreciable water movement through them." *Appreciable water* is usually taken to be enough water to supply a well or borehole. The definition of aquifer used in this document characterizes "appreciable" as meaning that there is sufficient water to sustain a dependent ecosystem even though the quality may not meet the standards set for human needs.

The term groundwater dependent ecosystem (GDE) is difficult to define and means different things in different countries. In some publications it has been used with emphasis on ecosystems that are found below ground, within the aquifer. For example Eberhard (2004) states that "*Groundwater plays a role in the ecological processes and "health" of many surface ecosystems, and is the critical habitat for subterranean aquatic animals (stygofauna)"*. A broader definition is given by Murray (2006) "*Groundwater-dependent ecosystems (GDEs) are ecosystems that must have access to groundwater to maintain their ecological structure and function*". However, where groundwater is not clearly defined there can be confusion between hydrologists and ecologists. The work carried out by Hatton and Evans (1998) suggest that groundwater is "*that water which (is or) has been below ground and would be unavailable to plants and animals were it to be extracted by pumping*". This does not then refer to groundwater in its hydrogeological sense, which would include inaccessible water in low permeability aquitards. Most of the current literature refers to GDEs based on an assumption that the groundwater is found in aquifers and able to be abstracted. In South Africa, we have defined the term **Aquifer Dependent Ecosystem** (ADE), because *aquifer* removes confusion about the primary water source and indicates that these ecosystems are vulnerable to the impacts of groundwater abstraction.

In summary:
Underground water may occur:

- in the unsaturated zone as soil water and interflow,
- in the saturated zone as groundwater in aquifers (extractable) and groundwater in aquitards and aquicludes (non- extractable).

Aquifer dependent ecosystems are ecosystems which depend on groundwater in, or discharging from, an aquifer.

2.2 A TYPE-SETTING APPROACH TO AQUIFER DEPENDENT ECOSYSTEMS (ADEs).

This handbook introduces ADEs in different type-settings in South Africa. The type-settings are a combination of different aquifer discharge settings and habitat settings. These specific combinations help us structure our understanding of these systems and classify them according to the aquifer - ecosystem interface. Table 2.1 shows the type-settings and the likelihood of their occurrence in South Africa.

Aquifers have different types of permeability, which develop as a result of the physical and chemical composition of the rock type and its geological and hydrological history. Figure 2.2 below illustrates the main types of permeability found in different rock types. Permeability is termed primary if it is formed as the rock is formed (intergranular) and secondary if it forms after the rock (fissures and caverns, fractures, joints and faults).

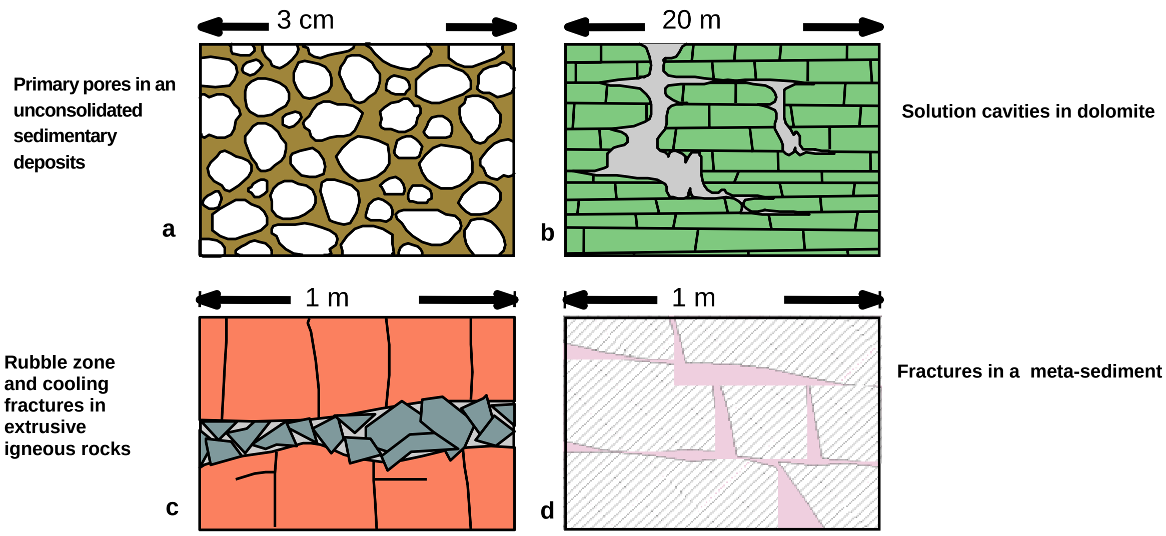
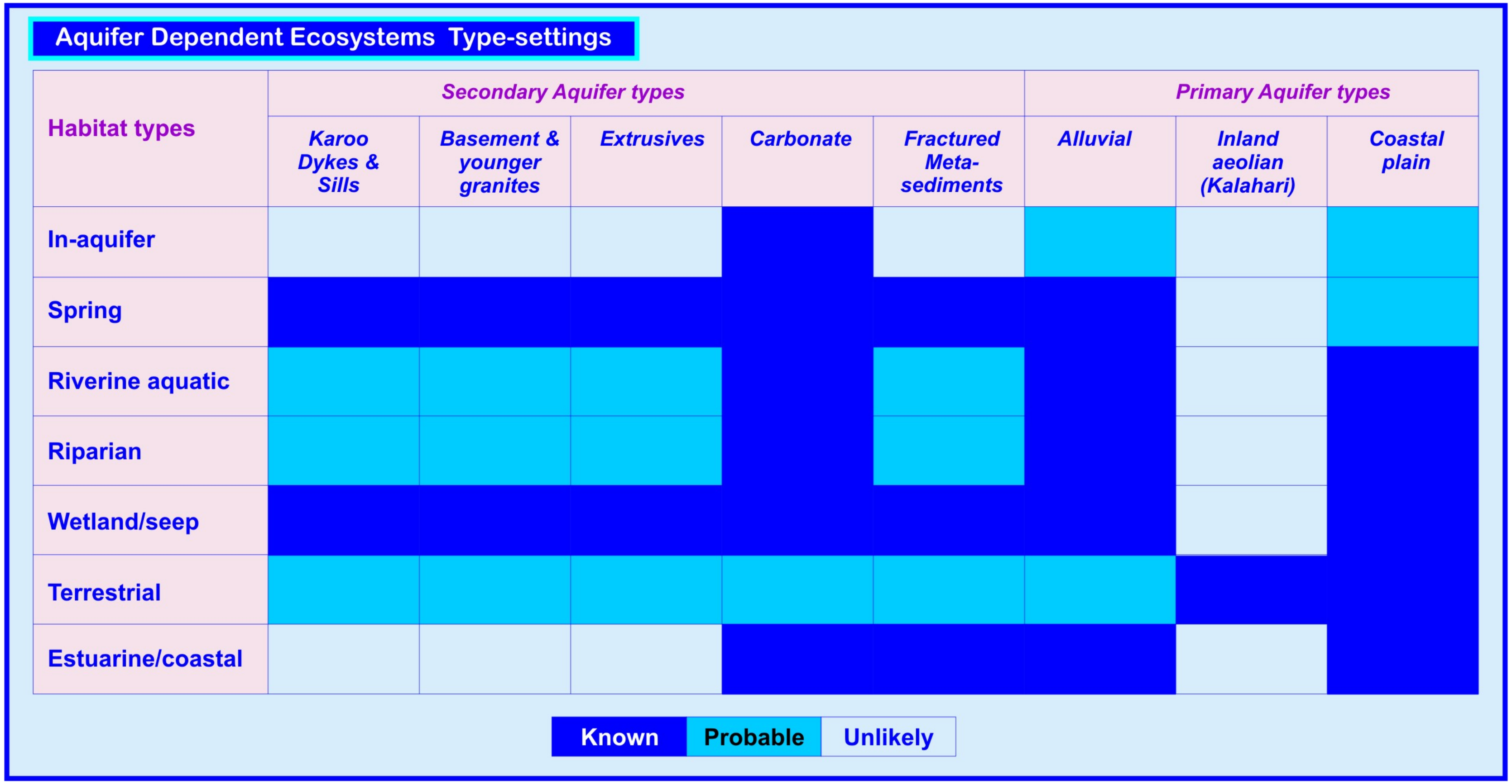


Figure 2.2: Different aquifer permeability types and scales: intergranular permeability in unconsolidated (primary) sediments; fissures in a carbonate dolomite; a cooling zone in an extrusive lava; fractures in a meta-sediment.

Different permeabilities result in different aquifer discharge patterns which supply groundwater to the surface environment. Fractured meta-sediment aquifers may discharge via discrete fractures or fault zones resulting in linear seeps or wetlands and discrete zones of discharge to rivers. An unconsolidated, primary sandy aquifer may have an extensive shallow water table supporting terrestrial vegetation or forming broad wetland areas.

Table 2.1: Typesettings for Aquifer Dependent Ecosystems in South Africa based on aquifer types and habitat types, with an indication of the probability of occurrence. The probability is defined as: Known = there are known occurrences of these ecosystem types in this setting; Probable = these types are likely to occur there but no data are available to confirm that; and Unlikely = these ecosystem types are unlikely to occur there.



Aquifer Dependent Ecosystems Type-settings

Habitat types	Secondary Aquifer types					Primary Aquifer types		
	Karoo Dykes & Sills	Basement & younger granites	Extrusives	Carbonate	Fractured Meta-sediments	Alluvial	Inland aeolian (Kalahari)	Coastal plain
In-aquifer	□	□	□	■	□	▨	□	▨
Spring	■	■	■	■	■	■	□	▨
Riverine aquatic	▨	▨	▨	■	▨	■	□	■
Riparian	▨	▨	▨	■	▨	■	□	■
Wetland/seep	■	■	■	■	■	■	□	■
Terrestrial	▨	▨	▨	▨	▨	▨	■	■
Estuarine/coastal	□	□	□	■	■	■	□	■

■ Known ▨ Probable □ Unlikely

Figure 2.3 shows the six main aquifer types in South Africa based on the aquifer properties of the main lithology (rock type) of the different rock strata. Appendix C lists the different geological formations and groups according to their rock type and age (litho-stratigraphy) which comprise these main types. This simplified geology enables a national scale view of the main aquifer types and gives an overview of which ADEs could be present based on the aquifer setting. In table 2.1 the unconsolidated primary deposits have been further sub-divided into alluvial, coastal and Kalahari.

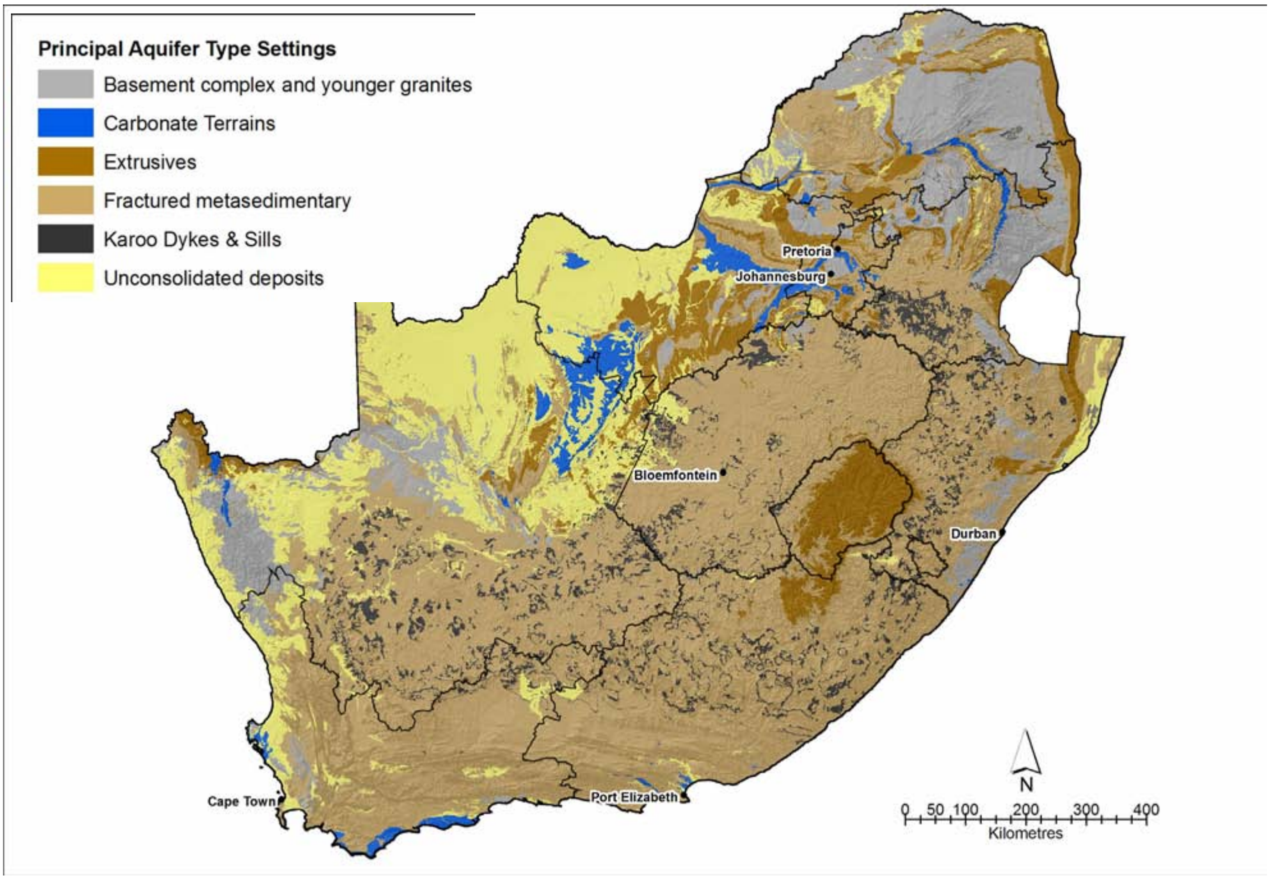


Figure 2.3: Map of main aquifer types based on primary lithology. (Source data – Council for Geoscience 1: 1000 000 lithology)

More than 90% of South Africa is underlain by hard-rock, or secondary, aquifers controlled by secondary faulting and jointing. These include the fractured metasediments, Karoo dolerites, extrusives and the basement. Primary (sandy) aquifers generally are restricted to the coast, alluvial and aeolian valley deposits (e.g. the Karoo) and the Kalahari.

ADEs occur through-out the landscape at various ecosystem scales. They are found in discharge areas of local and regional scale aquifer systems. They are represented across the continuum of habitat types from humid aquatic systems to arid terrestrial systems and do not, in reality, occur as discrete groupings used to classify ADEs. Riparian and hyporheic zones highlight the artificial distinction between aquatic and terrestrial and wetland ecosystems which, by definition, occur across the spectrum. However, the classification helps to order our understanding of complex interactions and group similar settings in a rational way. Figure 2.4 shows the different ADEs and where they occur in the landscape.

Figure 2.4: ADEs in the Landscape. (Source: Winter *et al.*, 1999)

2.3 WHY DO WE NEED TO UNDERSTAND ECOSYSTEM DEPENDENCY ON AQUIFERS

"Sustainable Use" of renewable resources such as groundwater, is the accepted aim of IWRM (see glossary) and recognises the fundamental right of people to water. This is usually taken to mean that a resource is used today and managed so that it will still be available to be used by future generations and that there are no long term negative impacts. In South Africa, groundwater should be used sustainably and stakeholders in the catchment should decide the levels of impact which are an acceptable consequence of using groundwater (within sustainable limits). If we are planning to pump water out of an aquifer or disrupt the flow regime or chemistry of an aquifer, we need to understand what the consequences of our actions will be. ADEs are very important in this respect, and we need to understand on which aquifers they depend and what is the nature of their dependency. With greater understanding of the ecohydrologic links in a catchment, the impacts of water use can be minimised.

ADEs are often ecosystems which contrast with their surrounding environment as a result of their access to groundwater. Often they occur at the transition of different ecosystems – an *ecotone* – and represent an important ecologic and hydrologic interface. They may form oases, riparian corridors or wetland habitats that support a much more extensive surrounding environment and function as *keystone* ecosystems. This is often the case in arid and semi-arid areas of South Africa. ADEs therefore may be particularly productive ecosystems which provide important ecological services and goods to communities.

Dependency

The degree or time scale of dependence can range from permanent to at least a portion of the dry season to only during extended droughts. Large shifts in community composition could be expected where changes in groundwater availability cross these thresholds, for example from permanently to seasonally available.

Normally we talk about dependency with respect to individual species, but we may discuss this concept with respect to the whole ecosystem:

- *Direct* dependence occurs where at least some of the species in the ecosystem require direct access to groundwater to be able to survive or complete their life-cycle.
- *Indirect* dependence occurs when species that can access groundwater sustain species that are not, themselves, able to access groundwater, or may depend in other ways on the species that can access groundwater.

A good example of indirect dependence is “hydraulic lift” - the process by which deep-rooted plants absorb water during the day and then release it from their shallow root systems at night (Richards and Caldwell, 1987). The additional water released into the surface soil layers may be critical for maintaining shallow rooted plants and any other dependent organisms in this kind of system. Hydraulic lift is likely to be present in many of semi-arid and arid zone environments where there are deep-rooted trees which can access groundwater. Research is underway at present to investigate whether *Acacia erioloba* in the Kalahari is capable of hydraulic lift and to determine the ecological importance of this phenomenon.

An example of *life-stage* dependence is seedling recruitment without which plant populations eventually senesce and become extinct. A high rainfall year is needed to stimulate seed germination and promote seedling recruitment in groundwater dependent phreatophytes such as *Prosopis* species (Harding and Bate, 1991) and *Acacia erioloba*. The rainfall wets the profile down to the water table to the extent that rapid root growth by the seedlings enables them to reach the capillary fringe above the water table before the soil layers above it dry out. The young plants are then no longer vulnerable to variations in rainfall.

3. TYPES OF SOUTH AFRICAN ADES

Research into South African ADEs is at an early stage. There are some existing bodies of research, especially on riparian zones and environmental flows for rivers and estuaries, which form an important contribution to the developing field of ADEs. This section gives an overview of the types of ADEs which are known and thought to occur in South Africa. They are described by their habitat or ecosystem setting: in-aquifer ecosystems, springs and seeps, riverine aquatic systems, riparian, terrestrial and estuarine and coastal. More detail on aquatic and terrestrial links to aquifers is given in Appendix A and B.

Figure 3.1 shows vegetation groups with a high, medium and low probability of being linked to aquifers. Figure 3.5 shows the calculated contribution of aquifers to surface water and aquatic ecosystems in rivers. Most wetlands, seeps and springs are too small to depict on a national map so only the extensive wetlands on the KwaZulu-Natal coast are visible in Figure 3.1.

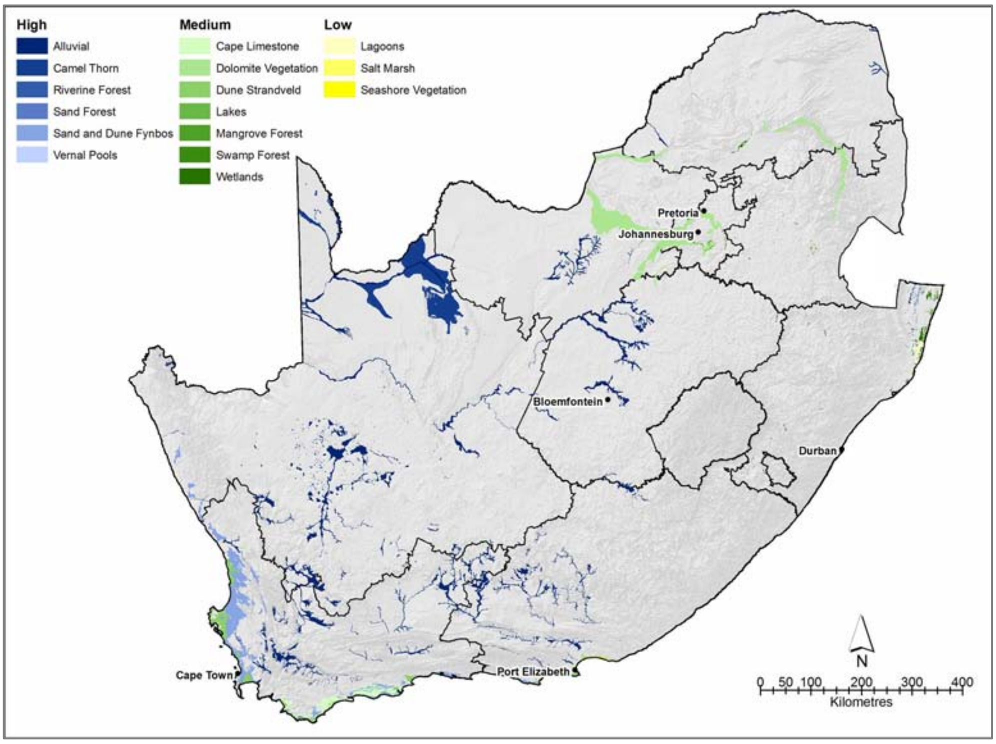


Figure 3.1: Groups of vegetation types with a high, medium and low probability of being aquifer dependent, based on the vegetation types in the national vegetation map developed by SANBI (Mucina and Rutherford, 2004). For more information see the text.

The list of vegetation groups below has been selected from the 441 vegetation types defined for the new vegetation map being prepared by the South African National Botanical Institute (Mucina and Rutherford, 2004). An initial list of 70 vegetation types was selected and grouped into 16 different categories. These are described within the habitat types outlined below. Descriptions of the 441 SANBI vegetation types are not available yet but a Beta version of the map is available with all the names of the different vegetation types (Mucina and Rutherford, 2004). The selection and grouping described below is based on the available literature on the different vegetation types, particularly the descriptions by Acocks (1976; 1988) and Low and Rebelo (1996) of similar vegetation types. The selection and grouping should be regarded as provisional and will be refined and finalised once the full descriptions have been published. The map should be interpreted in conjunction with Table 3.1 which indicates the broad types of ADEs that are likely to occur in those environments. The selection of these vegetation groups does not mean that other vegetation types do not have ADEs. The ones that were chosen were selected because (a) there is a higher likelihood that potentially dependent features (e.g. wetlands) are linked to groundwater rather than surface water or (b) the potentially dependent ecosystems may be particularly sensitive to the impacts of changes in groundwater availability.

Table 3.1: Vegetation groups associated with ADE type-settings.
For more information see the text.

Habitat types	Secondary Aquifer types					Primary Aquifer types		
	Karoo Dolerites	Basement	Extrusive	Carbonate	Fractured meta-sediments	Alluvial	Inland aeolian (Kalahari)	Coastal plain
Wetland/ seeps/ springs?	Wetlands	Mires Wetlands	Mires Wetlands	Dolomite Vegetation Cape - limestone vegetation Wetlands	Mires Wetlands Lakes Vernal Pools	Alluvial Wetlands Lagoons		Swamp forest Wetlands Seashore -vegetation Lakes Lagoons
Riparian		Riverine forest	Riverine forest	Riverine forest	Riverine forest	Alluvial Riverine forest	Riverine forest	Riverine forest
Terrestrial				Bo-Molopo dolomitic vegetation		Alluvial Camel thorn Sand forest Sand -fynbos	Camel thorn	Dune Strandveld Sand forest Sand fynbos
Estuarine/ Coastal						Alluvial Mangrove forest		Mangrove Lagoons Seashore - vegetation

3.1 IN-AQUIFER AND CAVE ECOSYSTEMS

In-aquifer and cave ecosystems are very low energy systems which occur underground and in areas with wide enough fissures or fractures. Research in this area is at an early stage in South Africa. However, they are known to occur in the dolomitic carbonates of South Africa

(Tasaki, pers.comm, 2003), and may occur in calcretised layers of sedimentary alluvial and coastal deposits and in the pseudo-karst fracture and cave systems of fractured aquifers. These systems lack plant species but can have a range of invertebrate fauna such as Amphipods, as well as a range of poorly known microbiota such as bacteria and fungi.

The dolomites in the north-western region of the country form South Africa's largest area of karst terrain (see Figure 2.3). Some of the cave systems in these dolomites have become well known worldwide because they include sites where remains of pre-historic hominid remains have been found. The most famous ones are at Sterkfontein and Makapansgat caves and now form part of the World Heritage Site known as the Cradle of Humankind. Data are currently being gathered on the species composition of the in-aquifer fauna of the dolomites in Sterkfontein in Gauteng (Tasaki, 2003, pers.comm).

Other cave systems include the well-known limestone Cango Cave system at Oudtshoorn and the sandstone cave systems on the Cape Peninsula. There are also limestone formations in the western and southern coastal forelands in the Western Cape but no ADE investigations have been done there yet. Amphipods have been seen in videos taken with a camera lowered down boreholes in faulted rock formations in the Tshipise area and a few other sites. There have been a few studies of cave ecosystems but systematic investigations of the fauna and functioning of these ecosystems are lacking.

Groundwater ecologists have developed a functional classification of aquatic (hyporheic) invertebrates based on where they live out their life-cycle in relation to surface and groundwater ecotones (Marmonier *et al*., 1993 in Hancock *et al*. 2005). This classification divides these organisms into three broad groups on their affinity to groundwater habitats:

- **Stygoxen** are largely confined to surface water but can enter subsurface environments such as the hyporheic zone or caves.
- **Stygophiles** are able to spend part of their life-cycle in the subsurface water but do not have specific adaptations to subterranean life.
- **Stygobites** have to have groundwater to complete their life cycles and have specific adaptations to do so.

3.2 SPRING AND SEEP RELATED ADES

Spring and seep ADEs are often closely linked to other habitat types such as riparian and wetland ADEs. They occur in most aquifer types of South Africa, excluding the unconsolidated Kalahari sands because the water table in this extensive primary aquifer is generally too deep for direct discharge as liquid groundwater. Where alluvial aquifers occur on impermeable bedrock they may support springs and seeps in this region.

Springs and seeps generally support relatively lush vegetation and in many areas are associated with biodiversity hotspots for plants, amphibians, birds and insects. In the Western Cape, groundwater fed springs at the Kammanassie Reserve also support the endangered Mountain zebra. Changes in spring flow are believed to have influenced river base flow and water stress in associated riparian species (Cleaver *et al*., 2003). The springs are species rich and 244 plant species from 145 genera were identified at four springs in the Reserve.

In the Kammanassie area the springs discharge water from the fractured metasediments (sandstones). The springs have been grouped into four classes according to their hydrogeological setting, as shown in Figure 3.2 below (Cleaver et al., 2003). This has helped researchers to assess the vulnerability of the springs and their associated ecosystems to climatic variability and abstraction.

Type 1:	Shallow seasonal springs and seeps emanating at perched water tables, which can be interpreted as interflow, seasonal flow or 'rejected recharge'. These springs are vulnerable to drought and climate change, but not to abstraction from the deeper aquifer. Approximately half the springs in the area are this type.
Type 2:	Lithologically Controlled Springs, due to the presence of inter-bedded aquitards. Examples occur at the contacts between the Peninsula and Cederberg, Goudini and Skurweberg and Nardouw and Bokkeveld. These springs are vulnerable to climate change and abstraction.
Type 3:	Fault Controlled Springs (FCS). These occur where groundwater flows along permeable fault zones. They may include deep flow paths and hot water springs (e.g. Calitzdorp, Brandvlei, Goudini). They are vulnerable to climatic variability and excessive abstraction.

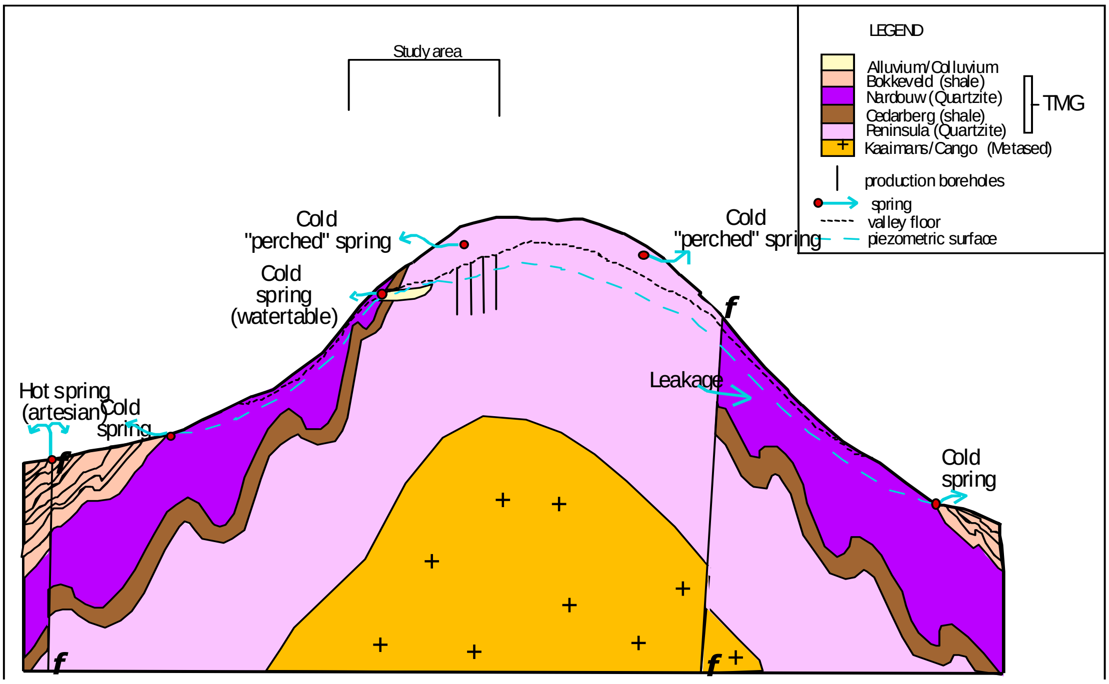


Figure 3.2: Schematic section of spring types in the Table Mountain Group (TMG) fractured metasedimentary aquifer at the Kammanassie Nature Reserve in the Western Cape, South Africa. (Source: Cleaver et al., 2003)

Springs, seeps associated with Karoo dykes and sills

Recent studies of the hydrogeology of Karoo dolerite suites have linked them to ecosystems (Chevalier et al., 2004). The various types of vegetation are shown in Figure 3.3. and the description below is summarised from Chevalier et al., 2004. Grassland is very common on high lying dolerite sills and this could be due to increased water availability via lower temperature and higher precipitation. These grassland areas are expected to be recharge areas with no perched wetlands or spongy areas. On the slopes of the dolerite rings Aloe-dominated thicket is predominant. These shrubs and succulents are adapted to more arid conditions than the grassy highlands and are not groundwater dependent. Lush tall shrubs with a tree component dominate in the kloofs and at the foot of dolerite cliffs and seem to prefer south and west-facing steep exposures. These luxuriant thickets may be partly phreatophytic i.e. a combination of moist conditions in valley or shadowy places and periodic use of non-perennial seeps at the base of dolerite cliffs.

Groundwater dependent plants occur around perennial seeps, mainly grass and sedges growing on peaty black soil forming small wet areas from a few metres to several tens of metres wide. Shrubs adapted to harsher conditions are unable to grow in these settings. They typically occur in depressions along fractures, or those created by morphological breaks.

The most hydrogeologically vulnerable ecosystems are the seeps occurring on the lower slopes which depend on discharge from the upper unconfined aquifer. Because of the high connectivity of these shallow fractures, poorly planned drilling can induce flows to lower aquifers, lowering the water table in the upper aquifer and reducing availability to these ecosystems. The location of wetlands or seeps at low elevation is therefore a major factor which should be taken into account when developing groundwater in this typesetting.

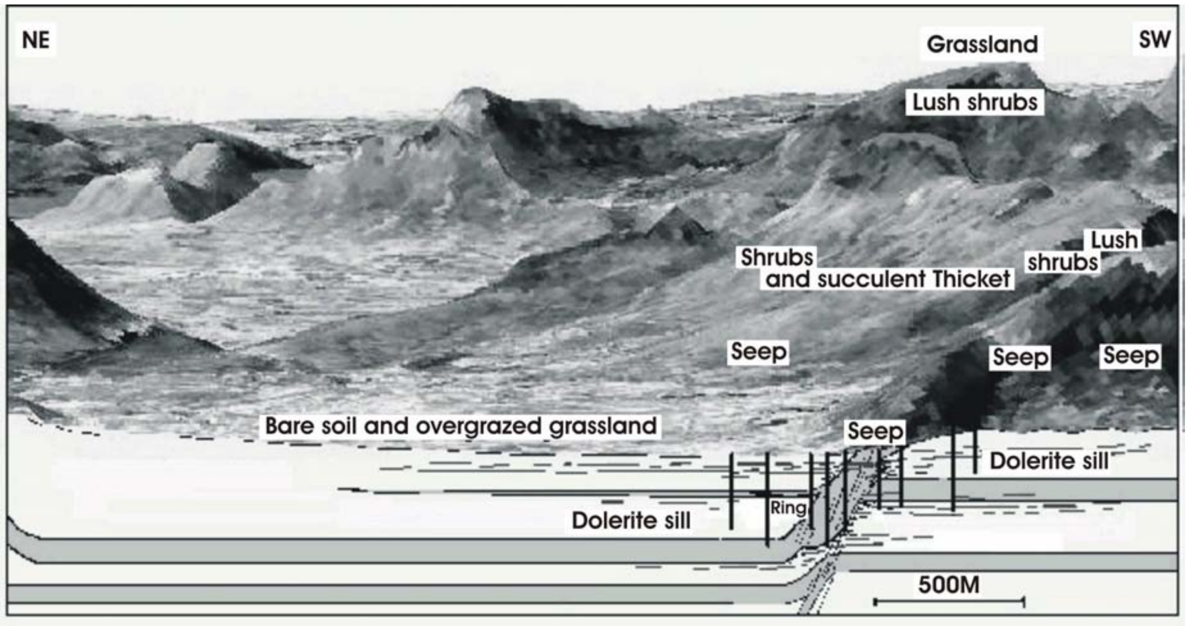


Figure 3.3: Landscape settings for seeps and ADEs linked to discharge from Karoo dyke and sill suites. (Source: Chevalier et al., 2004)

Vernal Pools

Vernal[1] pools are a specific type of seasonal or ephemeral pool which occurs in Mediterranean climates (winter rainfall areas) (Keeley and Zedler, 1998) and are known for their abundance of spring flowering plants. They are recognised as a specific vegetation type in the SANBI vegetation map (Mucina and Rutherford, 2003). They appear to depend on aquifers as they have no connections with river systems and occur in situations where there is not enough surface or interflow discharge to maintain them through the dry season (summer and autumn). They are relatively rare in South Africa and the only ones that have been mapped are in the lowlands on the west coast in the Western Cape Province (fig 3.1).

3.3 WETLANDS

Groundwater-fed wetlands, like springs, are known to occur on all the main aquifer typesettings in South Africa, excluding the Kalahari sands. Wetlands and springs are often

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[1] Vernal means the season of spring and is used here in the sense of the season of the year in which they are most evident.

grouped together because there often isn't a clear distinction between them. This is particularly true in secondary aquifers such as those associated with dykes and sills, fractured rocks and the basement. A spring typically has a distinct discharge point whereas wetlands tend to have a more diffuse area of discharge. Wetlands fed by alluvial aquifers are often closely linked to the riparian zone and those on the coastal sands to estuarine and coastal brackish habitats.

Under the South African National Water Act (1998) a wetland is defined as "*land which is transitional between terrestrial and aquatic systems where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil*." This definition links wetlands to groundwater and unconfined (phreatic) aquifers through the use of 'water-table' as one of the possible defining features. However, many wetlands occur as a result of surface rather than sub-surface drainage and ponding on low permeability soils. It is important to understand whether wetlands are linked to aquifer discharge areas before classifying them as groundwater (or aquifer) dependent.

Information available on wetlands generally does not indicate the source of the water in the wetland, so wetlands which appear to be linked to aquifer discharge zones need to be investigated to determine the relationship between them and the local aquifers. The hydrology of a wetland needs to be understood in terms of whether or not it is:

- a source or sink of groundwater,
- a source or sink of surface water?

These relationships may be dynamic and change with the season.

Research is being done on the relationships between groundwater and wetlands in the Table Mountain Group and there is some information on groundwater and highveld wetlands (Marneweck and Batchelor, 2002; G. Marneweck pers. comm. 2004), and groundwater and Lake St. Lucia (Ellery and Kelbe pers. comm. 2004) and further work is being carried out (in conjunction with Working for Wetlands) to develop a better understanding and more reliable guidelines.

Wetlands in the dolomites

Wetlands associated with both sinkholes (points of recharge) and springs (points of groundwater discharge) are very important aquatic features in the dolomitic karstic area of South Africa, which is dominated by the dolomite aquifer. Due to the relative geographical isolation of these habitats, many of the springs and wetlands sustain rare or endemic flora and fauna (Stephens et al., 2002). The flow regime of the South African dolomites, and therefore the occurrence of wetlands, is largely controlled by low-permeability contact (e.g.

dykes) which compartmentalise the carbonates as shown in the schematic cross-section (Figure 3.4).

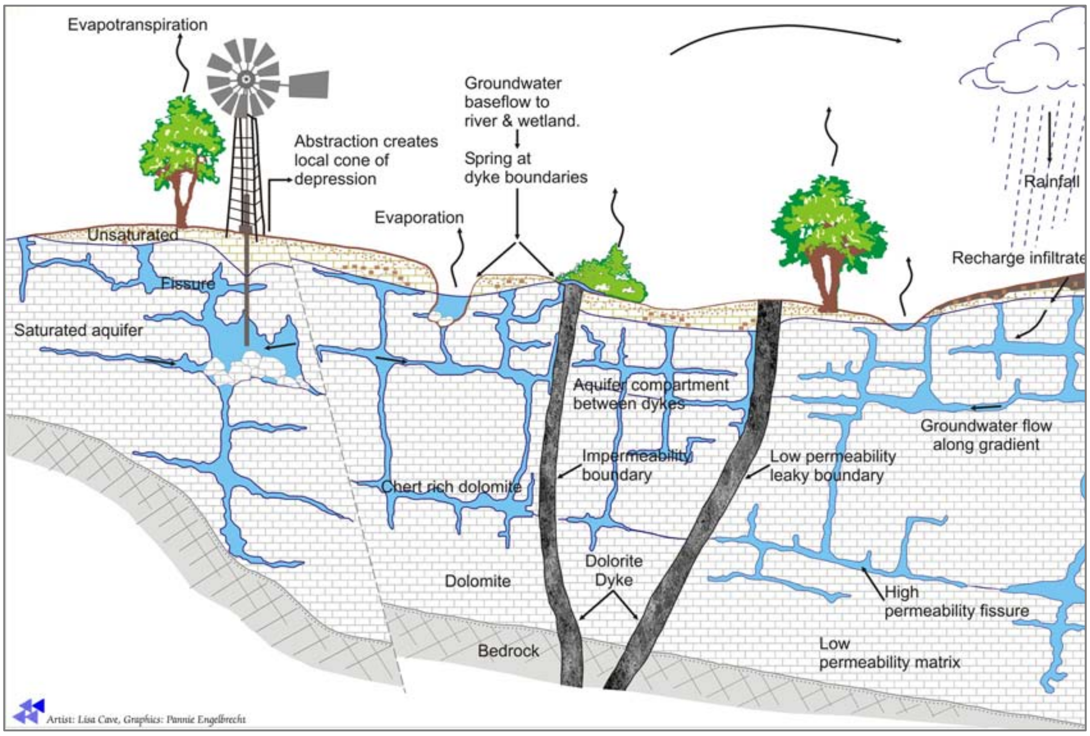

Figure 3.4: Schematic cross-section of the dolomitic aquifer of North-West Province, South Africa.

Dolomitic eyes commonly support ecological communities which have evolved independently of one another, driven by particular local factors (e.g. temperature, flow etc). For example, the algal and diatom community in the Molopo Eye is different to that at the Malmanies Eye, indicating that each eye could be a unique ecosystem (Nel et al.,, 1995). Distinct morphological and behavioural changes have been recorded in the *Pseudocrenilabrus philander* (southern mouthbrooder) and *P. crenilabrus* in the various eyes indicating species specification. Dolomite eyes are highly sensitive to invasion by exotics (e.g. Black bass) and indigenous species are sensitive to the introduction of alien predatory fish due to the very clear water.

Other wetland vegetation

The wetland vegetation group is made up of a wide variety of wetland types (e.g. vleie, marshes, mires), which have been grouped into broad regional types in the SANBI vegetation map for an overview of wetlands in South Africa). This makes it very difficult to distinguish those types, probably relatively few, which we would expect to be dependent on groundwater from those we would expect to be dependent on other sources of water, probability the majority.

Lakes

There are very few natural freshwater lakes in South Africa, with most of them being found on the Zululand coastal plain and the Wilderness area in the southern Cape. Most of them are linked with river systems but they also have a degree of dependence on groundwater baseflow from the surrounding primary aquifers. Lakes which are not connected with river systems, such as Lake Sibaya, are more directly linked to the associated aquifers and dependent on them. Groundwater may also play an important role in maintaining refugia for freshwater organisms in Lake St Lucia during periods when salinities are high.

3.4 RIVERINE AQUATIC ECOSYSTEMS

South African rivers have been classified in terms of their geomorphology, ecology, climate and geology (e.g. ecoregions – Kleynhans, 1999), but they have not yet been comprehensively assessed in terms of their relation to aquifers. Licenses for use of surface or groundwater may not been issued until the quantity and quality of water required to maintain aquatic ecosystems has been determined. This water is known as the Reserve. This new legislation has stimulated research into the interconnections between rivers and aquifers. Appendix A discusses surface water – groundwater interactions in more detail.

3.4.1 Aquifer – surface water interconnections

Based on their runoff characteristics, streams can be classed as Ephemeral, Intermittent or Perennial. Vegter and Pitman (1996) build on this classification, to propose a classification that also considers the characteristics of the groundwater-surface water interaction in that stream or river. The classification is based on the streams’ relation to the piezometric head in the aquifer systems with which it is in hydraulic connection and indicates whether water is moving into or out of the aquifer. The river classes are (Vegter and Pitman, 1996):

Influent: The piezometric surface is at all times below the stream bed level, where the material between the stream bed and the aquifer is pervious, with the piezometric surface sloping downward away from the stream. The stream acts as a sink and recharges groundwater.

Detached: The piezometric surface is at all times below the stream bed level, where the material between the stream bed and the aquifer is more or less impervious, with very little or no recharge of the aquifer.

Effluent: The piezometric surface slopes laterally down towards the stream, where groundwater reaches and emerges into the stream at all times. The piezometric surface at the stream is permanently above the stream stage, and the material between it and the streambed is pervious – porous or fractured. The stream acts as a drain or sink.

Intermittent: The piezometric surface slopes laterally down towards the stream, where groundwater emerges into the stream at intervals, i.e. for a while after recharge episodes. During dry periods groundwater storage is depleted by the effluent or in combination with evapotranspiration from the stream banks and within the catchment. Groundwater may be replenished to a certain extent in the immediate vicinity of the stream by storm runoff.

Famished: The piezometric surface slopes laterally down towards the stream, where groundwater does not reach the stream, because it's permanently being dissipated along its flow path towards the stream by evapotranspiration.

In-/effluent: The piezometric level fluctuates alternately above and below the stream stage. The stream is underlain and bordered by alluvial deposits and/or porous decomposed rock.

Though the designation of Vegter and Pitman (1996) cannot necessarily be applied to full length of all rivers, with different stages of most rivers displaying different characteristics, there are some rivers to which the general classification can be applied.

The following are Southern African examples of such streams/rivers (Vegter and Pitman, 1996):

Influent:	Kuruman River, downstream from at least Flylincks Pan. Molopo River, downstream from at least Tshidilamolomo.
Detached:	Relatively steeply graded and dry, rocky stream beds particularly in the arid northwestern parts of the country.
Effluent:	Upper reaches of perennial rivers rising on the eastern escarpment, such as the Vaal, Olifants, Tugela, Blyde, Komati, etc.
Intermittent:	Streams in the Karoo, such as the upper reaches of the Salt River (Beaufort West), the Kamdeboo, Sundays and Brak Rivers (De Aar).
Famished:	Rocky sections of the Limpopo River, for example the alluvium-free stretches between Stockpoort 1 LQ and Sannandale 9 LQ; and the steeper graded section between the junctions with the Lephalala and Motlouse Rivers.
In-/effluent:	Wide stretches of relatively unexploited alluvium along the Limpopo River between the confluence of the Marico and Crocodile Rivers and its junction with the Mahalapswe River.

Groundwater fed baseflow

In most natural river flow systems, the low flow or baseflow is maintained by groundwater discharge from aquifers. Figure 3.5 shows the calculated groundwater fed baseflow (under virgin conditions) as a percentage of total flows (DWAF GRAII, 2005). The GRAII calculation of groundwater-fed baseflow took into account interflow-fed baseflow.

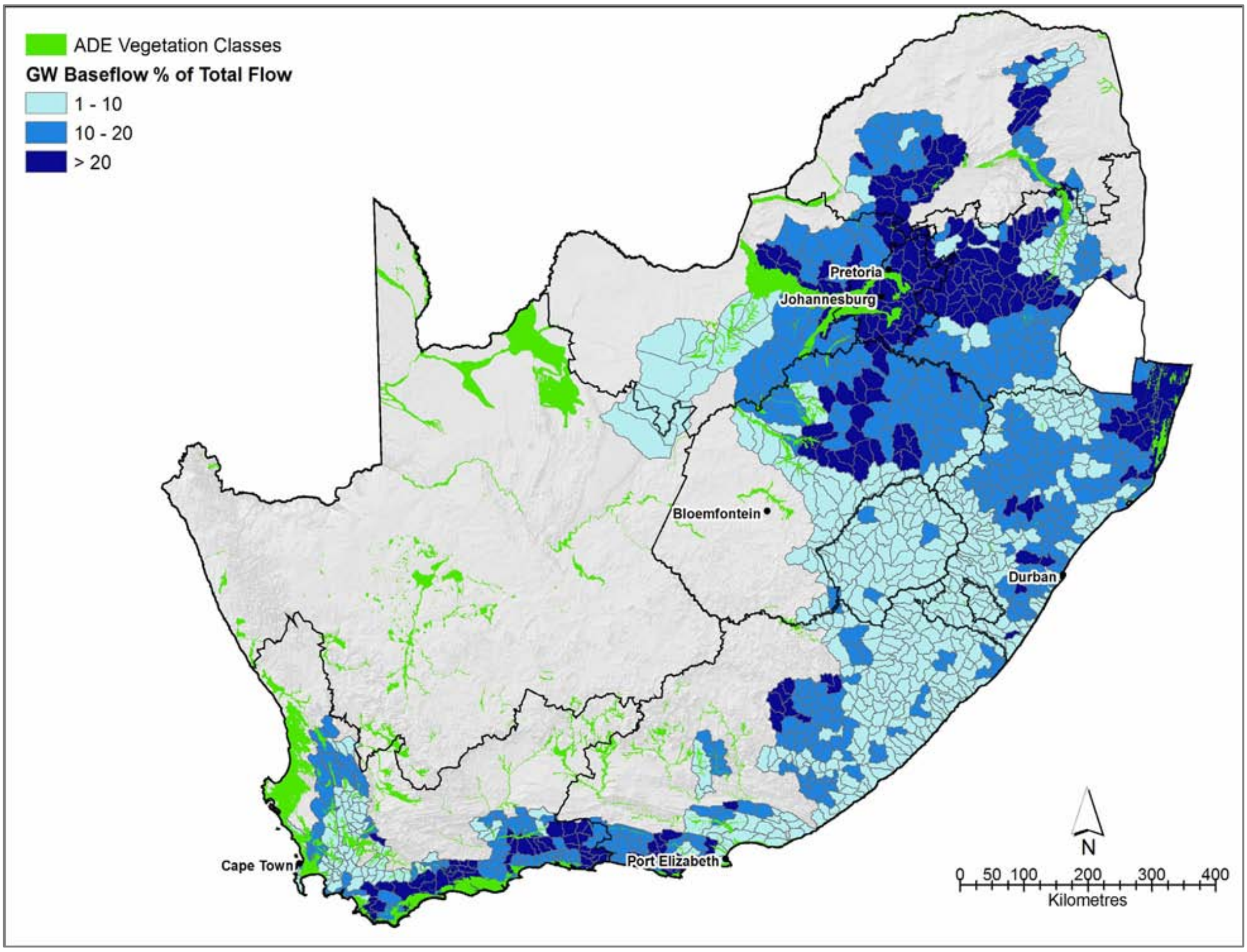

Figure 3.5: National scale indication of terrestrial ADEs (based on NBI vegetation classes) and aquatic ADEs (based on GRAII calculated Groundwater-fed Baseflow as a percentage of total flows in quaternary catchments in South Africa).

Peak flows and aquifer discharge

Although groundwater contribution to base flow is generally regarded as the most critical role of aquifers in surface water systems, groundwater also contributes to peak flows. Interactions between groundwater and surface water are typically dynamic depending on the hydraulic and topographic gradients (Woessner, 2000). Thus a river may be losing water to the aquifer at high flows and gaining water at low flows and the situation may vary along the length of a river. For example, the Orange River is a gaining river for the upper half of the catchment but is a losing river for the rest, as are many of the other rivers which rise in the montane regions (e.g. along the escarpment) and flow through more arid regions.

Groundwater also may contribute to peak flows in rivers via displaced subsurface water during rainfall events. This means that a component of storm flow may pass through the associated aquifer. Research shows the water stored in the subterranean environment system prior to the current rainfall (pre-event water) varies between 40 and 80% of the post-event river flows in humid temperate regions and 25 to 35% in semi-arid regions. Various factors appear to influence the response of catchments to rainfall events, including climate, soil thickness, soil structure topography, vegetation and geology (McDonnell, *et al*., 1990, Midgley and Scott, 1994, Sandström, 1996).

In some river systems with alluvial beds there are permanent pools which are maintained by groundwater discharge from the surrounding aquifer. These pools often occur where there is a rock sill formed by a dyke or by vertical displacement along a fault line.

Table 3.2: Fish species associated with perennial rivers and groundwater fed baseflow to riverine ecosystems, and fish species associated with alluvial springs in non-perennial rivers of northern South Africa. (Kleynhans, pers.comm. 2005).

Fish species typical of perennial rivers, they need flowing water during all phases of their life-cycle	**Fish species typical of non – perennial systems with alluvial springs (permanent pools?)**	
Chiloglanis pretoriae *Chiloglanis emarginatus* *Chiloglanis anoterus* *Chiloglanis bifurcus* *Chiloglanis swierstrai* *Amphilius natalensis* *Amphilius uranoscopus*	*Clarias gariepinus* *Oreochromis mossambicus* *Labeobarbus marequensis* *Barbus paludinosus* *Barbus afrohamiltoni* *Barbus trimaculatus* *Barbus unitaeniatus* *Mesobola brevianalis* *Micralestes acuditens* *Brycinus imberi* *Schilbe intermedius* *Chiloglanis paratus*	*Anguilla mossambicus* *Tilapia sparmanii* *Pseudochrenilabrus philander* *Tilapia rendalii* *Synodontis zambezensis* *Labeo cylindricus* *Labeo molybdinus* *Labeo ruddi* *Labeo rosae* *Aplochelichthys katangae* *Aplochelichthys johnstoni*

Sabie-Sand River

An example of a riverine ecosystem where groundwater discharge sustains key ecosystems is the Sabie-Sand River system. The sources of this river system are in the mountains along the Drakensberg escarpment in Mpumalanga and the tributaries flow through plantations, irrigated farms and rural areas before passing through Kruger National Park and continuing through Mozambique to the Indian Ocean. Base flow discharge from the upper catchment, primarily groundwater (Birkhead *et al*., 1997), keeps this river perennial.

Most of the studies of this ecosystem have focused on documenting the flora and fauna and the role of the hydrodynamics of different kinds of river flows in shaping the river floodplain, proportions of rocky and sandy river bed, and tree species distributions and recruitment (Birkhead *et al*., 1997; Jewitt *et al*., 1998). The area has relatively low rainfall and the riparian forest is sustained by river discharge into the river bank aquifer. The riparian forest and associated vegetation play key roles in maintaining the biodiversity and functioning of the adjoining terrestrial ecosystems (Davies *et al*., 1993; Jewitt *et al*., 1998).

3.4.2 Hyporheic zone

The saturated zone of mixing between groundwater and surface water below rivers and streams is known as the hyporheic zone (Stanford and Ward, 1988; Woessner, 2000). This zone represents an ecotone between the surface environment characterised by light, high dissolved oxygen and temperature fluctuation, and the groundwater environment characterised by darkness, less oxygen, stable temperature (Hayashi & Rosenberry, 2002; Hancock *et al*., 2005), and interstitial spaces. Some of the species found in in-aquifer ecosystems removed from surface water, are linked to hyporheic zone ecosystems.

The hyporheic zone provides a number of ecologically important services. These include:

- thermal, temporal and chemical buffering of water moving between groundwater and surface water;
- providing habitat for micro-organisms, macro-vertebrates, fish and wildlife;
- sustaining of refugia for aquatic species that rely on a particular chemical or temperature regime for their survival; and
- supplying nutrients and inorganic ions to surface water systems through groundwater discharge.

It is expected that aquifer discharge and mixing with surface water will play an important role in controlling the physio-chemical environment of the hyporheic zone in many South African river reaches in the middle and lower catchments, where surface flow is slower.

3.5 RIPARIAN ECOSYSTEMS

Riparian ecosystems are associated with groundwater dependency in a range of aquifer types, but most importantly with unconsolidated alluvial aquifers. These form important keystone ecosystems in the semi-arid and arid areas of the country, particularly where surface flows are seasonal and ephemeral.

The riparian forest ecosystems appear to be quite sensitive to changes in groundwater levels. During the period from 1979/80 to 1982/83 flows in the Kuiseb River in Namibia did not reach its delta, and the piezometric surface in the alluvial aquifer dropped by 3 m (Ward & Breen, 1983). A number of large *Faidherbia (Acacia) albida* trees (riparian fringe woodland) died and the growth and vitality of riverine vegetation declined. Localised stands of young *F. albida* (established in 1974 and 1976) did survive suggesting that the large dead trees had lost their ability to adjust to the lowering of the water table. *Acacia erioloba*, a species which also occurs in non-riparian habitats, did not show any signs of mortality, presumably because it is better able to track changing water tables. Ward and Breen (1983) suggested that the young *F. albida* trees were able to keep their roots in contact with the falling water table unlike the mature trees. Subsequent work suggests that the older trees were dying naturally due to their old age and not due to their inability to adapt their root systems (D Ward personal communication, 2001). The trigger for the deaths was a natural drought but its effects were exacerbated by dams in the upper reaches which reduced flows and altered flood frequencies.

Riverine Forest

This type of vegetation is confined to the larger river systems of the lowveld, from the Limpopo to northern Kwa-Zulu Natal. The forests occur on alluvial deposits in the floodplain (macro-channel) of the rivers. The forests are generally characterised by large trees and include species such as *Faidherbia albida* (Ana tree), *Acacia xanthophloea* (Fever tree) *Ficus sycomorus* (Sycamore fig), *Diospyros mespiliformis* (Jackal berry), *Lonchocarpus capassa* (Appleleaf) and *Xanthoxercis zambesiaca* (Nyala tree). The dominant type of ADE is riparian alluvium where the trees, in particular, are utilising groundwater stored in the alluvial deposits in the floodplains. These aquifers are recharged by periodic floods and also, potentially, by lateral groundwater inflow from the adjacent areas and sub-surface flow in the active channel, fault systems and fractures associated with dykes crossed by the rivers. The Limpopo River is a good example of a combination of Riverine Forest and alluvial ADEs.

The Limpopo riparian zone

Figure 3.6 shows a Landsat image of the Limpopo valley between South Africa and Zimbabwe, and its tributary the Shashe, showing relatively lush areas in red (high Normalised Difference Vegetation Index). The lush vegetation is either irrigation-fed (groundwater source) and distinguished by the circular shape of the pivot irrigated areas, or reliant on groundwater discharge from the alluvial aquifers of the Limpopo and its tributaries. The dark purple area in the north, in Zimbabwe, is underlain by basalt.

It is estimated that in excess of 10 million m^3 are abstracted annually from the alluvial aquifer shown in Figures 3.6 and 3.7, for both irrigation and mining. A mining company, which is one of the larger abstractors on this stretch of river, has monitored seasonal water stress in selected riparian trees (*Ficus sycamorus* and *Croton megalobotrys*) as part of their licensing conditions for groundwater abstraction since 1991. The company have redesigned their alluvial well-field to reduce interference effects between pumping wells and thereby reduce draw-down impacts on dependent tree species.

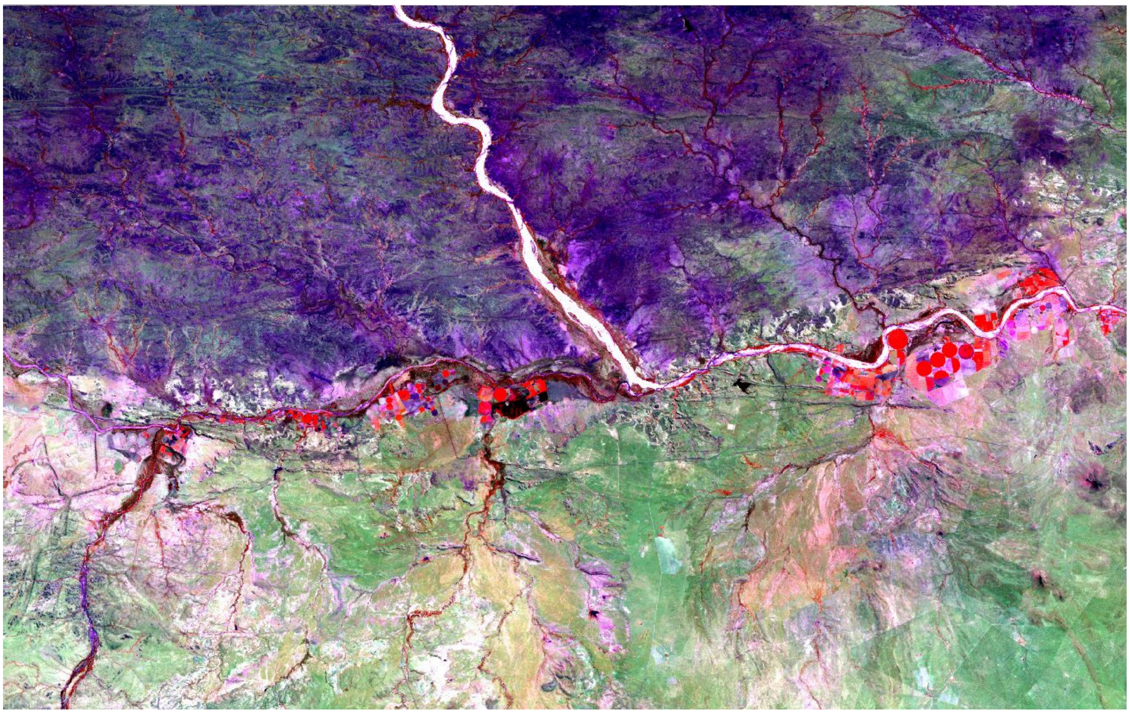

Figure 3.6: NDVI RS image of the Limpopo valley between South Africa and Zimbabwe showing relatively lush areas in red.

ADE health is particularly important in this trans-boundary area where it forms an important keystone ecosystem. It is an important political issue as Botswana, Zimbabwe and South Africa intend to strengthen their eco-tourism concerns in this area with a trans-frontier conservation area (TCA). There is also growing demand for water for human-use and irrigation from this internationally shared aquifer and the main water source is the groundwater in the alluvial aquifer.

Figure 3.7: Drilling water supply boreholes on the banks of the seasonal Limpopo river. The view looks north from the South African bank to the riparian vegetation on the Zimbabwean bank in this trans-boundary ADE.

3.6 TERRESTRIAL

Terrestrial ADEs are those where there is no direct groundwater discharge at the soil surface but the water table is within reach of components of the ecosystem. This form of interaction is also called “cryptic” discharge (Hatton and Evans, 1998). In most cases the connection is via the root systems of the plants, particularly the deep-rooted woody plants such as shrubs and trees. If the water table is too shallow for the typically deeper-rooted woody species, then they will be replaced by herbaceous growth forms including grasses, sedges and reeds or bulrushes more typical of wetlands. Cryptic discharge in terrestrial habitats has been noted in South Africa on Kalahari and coastal sands and fractured aquifers. More detail is provided in Appendix B.

Camelthorn

These vegetation types are found on Kalahari sands and are characterised by the abundance of *Acacia erioloba* (Camelthorn), a species which is sensitive to changes in depth to the water table. This ecological keystone species can have very deep root systems (30-60 m) and is most common in alluvial settings where it forms gallery woodland or forest. The dominant ADEs would be the terrestrial type and they occur mainly in alluvial situations and areas where the water table is relatively shallow, as described for the alluvial typesetting above). There are areas where *Prosopis* (mesquite) species have invaded and there is competition for groundwater which is placing the trees under stress. Typical tree species in these environments include: *Acacia albida, Acacia erioloba, Acacia haematoxylon, Acacia karoo, Rhus lancea, Tamarix usneoides, Euclea pseudebenus, Salvadora persica, Ficus sycomorus* and *Ficus cordata*.

There is a growing body of research which has found that these trees - singly, in stands and as gallery forests - are *keystone ecosystems* (Dean *et al*., 1999; Milton and Dean, 1999) The trees provide an environment which supports a rich insect fauna (>700 species in a survey of a section of the Kuiseb River in Namibia) (Prinsloo, 1990). The gallery forests and associated vegetation sustain a rich vertebrate fauna, including reptiles, birds and large mammals. The large ungulates complete the cycle by dispersing the seeds and possibly scarifying the seed coast to enable them to germinate more readily. These deep-rooted species are thought to act as nutrient pumps but it is equally likely that they are providing water to shallower-rooted plants via hydraulic lift. These ADEs provide key resources for the local human populations as well as for the farmers and the mines.

Sand-plain fynbos

Sand-plain fynbos is a form of the species rich Cape fynbos (fine-bush) which is found where there are deep, unconsolidated, acid sand deposits on the western and southern coastal lowlands in the Western Cape (Low and Rebelo, 1996). It is very similar to the kwongan vegetation on similar substrates in Western Australia. This kind of fynbos is characterised by an overstorey (3-5 m tall) of deep-rooted Proteaceae and an understorey and ground layer with a rich flora of woody and herbaceous species, many of which are endemic to these communities. These areas are also associated with shallow (<10-20 mbgl) groundwater and are probably groundwater dependent like the analogous systems in Western and south-eastern Australia. Studies have shown that higher leaf area indices and lower levels of moisture stress are evident in sand-plain or strandveld areas where the water table is around 5 mbl as opposed to 14 mbgl (Colvin et. al., 2003a).

Dune Strandveld

This is vegetation group consists of evergreen shrub vegetation which is found on deep, regic dune sands which may contain primary aquifers and is similar to the Dune Thicket of Low and Rebelo (1996). Small scale wetlands and springs may also occur within this predominantly terrestrial habitat. A range of vegetation types are found within this group along the coast from the Western to the Eastern Cape. Common trees include *Mimusops caffra* (Coast Red Milkwood) and *Sideroxylon inerme* (Milkwood) which are known to be indicators of groundwater. The groundwater dependence is likely to be lower than that of Sand and Dune Fynbos as the dominant shrub species are believed to be tolerant of moisture stress. The tree species such as the Milkwoods may be sensitive to moisture stress caused by changes in the availability of groundwater.

Sand Forest

Sand forest is found along the coastal belt of KwaZulu-Natal, mainly in the inland sand flats from Mtunzini northwards, and in the sandveld of the northern Kruger National Park. It is similar to the Sand Forest described by Low and Rebelo (1996) and by Midgley et al. (1997). It is found on deep sands and it is likely that the deeper rooted species are in contact with the primary aquifers which occur in theses environments. The vegetation is characterised by the dominance of tropical, deciduous to semi-deciduous elements, especially in the canopy layer which makes it different from the more widespread coastal forests. Where species in this forest are in contact with groundwater they would be vulnerable to changes in the depth to the water table.

3.7 ESTUARINE AND COASTAL ECOSYSTEMS

Estuarine ADEs are known to be important in the unconsolidated coastal sand aquifers of South Africa, but are also linked to other aquifer types where they discharge at the coast. For instance the alluvial aquifers of the north west coast feed brackish wetlands in arid areas with ephemeral surface water flow, e.g. the Buffels River close to the Namibian border and the desolate skeleton coast.

On the humid east coast, groundwater in the extensive coastal sands feeds lakes and wetlands in northern KwaZulu Natal. Lake Sibiya, Lake Mzingazi and the St Lucia wetlands are examples where detailed monitoring of relative groundwater heads and lake levels and the hydrochemistry have indicated the importance of groundwater inflows (Kelbe *et al.*, 2001). Relatively fresh groundwater discharge to these systems often maintains brackish refugia habitats during high salinity periods. Groundwater discharge into mangrove areas further north in Mozambique, has been found to influence the distribution of mangroves in Maputo Bay (Paula, 2001) and this may be the case for the more limited mangrove areas in eastern South Africa.

Mangrove Forest

Mangrove forests occur on the east coast of South Africa from the Eastern Cape to Kosi Bay, with the most extensive forests being at Durban harbour and Richards Bay. Overall dependence on groundwater is likely to be low but may be higher at key life stages, for example seedling recruitment of mangrove trees. The main source of freshwater is from the river estuaries where they occur but groundwater may play a role during periods when the mouth is closed. The availability of groundwater is thought to be the reason why freshwater terrestrial vegetation can occur on the inland edge of the mangrove forest, without an intermediate salt marsh but more research is needed to understand the roles groundwater plays in these settings.

Swamp Forest

Swamp forests are found only on the sandy coastal plains of Kwa-Zulu Natal, from Mtunzini northwards to the Mozambique border (Low and Rebelo, 1996). The swamps occur in the lower-lying areas of the plains, usually in association with river systems and where the ground water level is above the surface. The degree of dependence of groundwater is unknown but is expected to be highest for those systems which do not have a significant surface water catchment.

Seashore vegetation

This group comprises the vegetation of rocky shores and is characterised by the presence of a limited set of salt-spray tolerant species. For an overview of coastal vegetation in South Africa, including rocky shore see Lubke *et al*. (1997). Groundwater dependent ecosystems will be relatively rare and confined to settings where the rocky shoreline is the bedrock and groundwater is discharging over the surface of the bedrock or through fracture systems in the bedrock. The dominant ADEs will be springs, seeps and wetlands - where the water-table is shallow enough for wetlands to develop.

Lagoons

Lagoons are thought to require groundwater to prevent them becoming too saline for fresh and brackish water related species and ecosystems to survive. During the rainy season most lagoons receive more surface water inflow than groundwater as well as seawater interchange through the lagoon mouth. During the dry season or when the mouth is closed, groundwater might be critical for maintaining at least some of these systems.

Langebaan lagoon is an example of an aquifer dependent lagoon as groundwater inflow at the southern end is the only source of freshwater for this system. The discharge zone from a coastal sand and calcrete aquifer, the Elandsfontein aquifer, is greatest where the aquifer is thickest in an infilled palaeochannel. In this area in the intertidal zone *Phragmites australis* reeds occur. Figure 3.8 shows a conceptual cross section with groundwater flow paths discharging towards the reed beds and the lagoon bottom. *Phragmites* cannot tolerate the marine salinity found in the lagoon (35000 mg/L) in the rooting zone. Typically they require brackish porewater of <15000 mg/L, therefore it is postulated that the only possible source of freshwater for the rooting zone of these plants is groundwater discharging from the aquifer. Figure 3.9 shows how the resistivity of the sub-surface is different beneath the different vegetation types, and this may be due to greater volumes of fresh porewater in the aquifer discharge zone. The vegetation seen in the lagoon is in fact typical of an estuary (Whitfield, 2005), therefore Langebaan lagoon may be an aquifer-fed estuary.

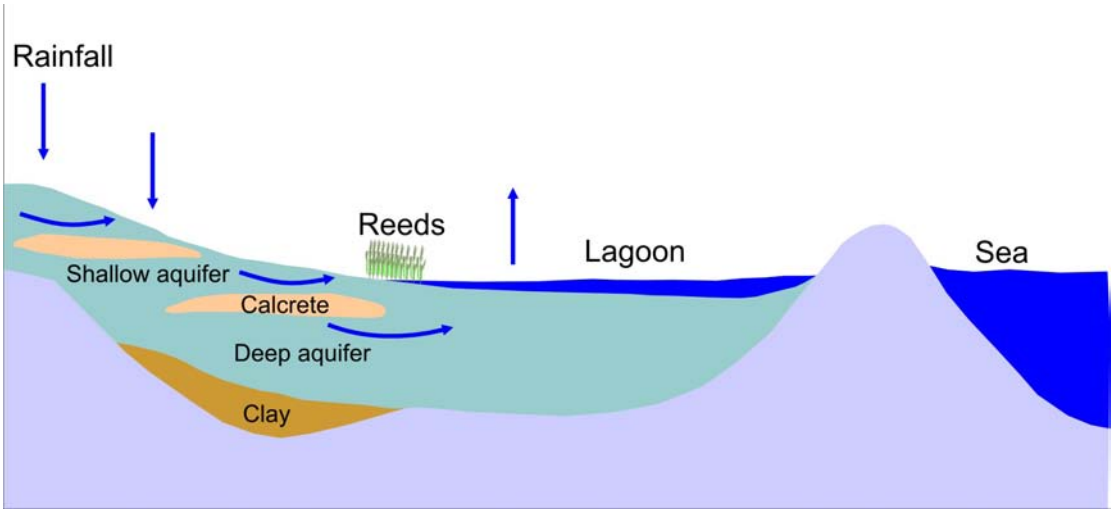

Figure 3.8: Conceptual cross-section of Langebaan lagoon showing groundwater flow paths from the sand and calcrete aquifer discharging to *Phragmites* reed beds in the intertidal zone and towards the lagoon.

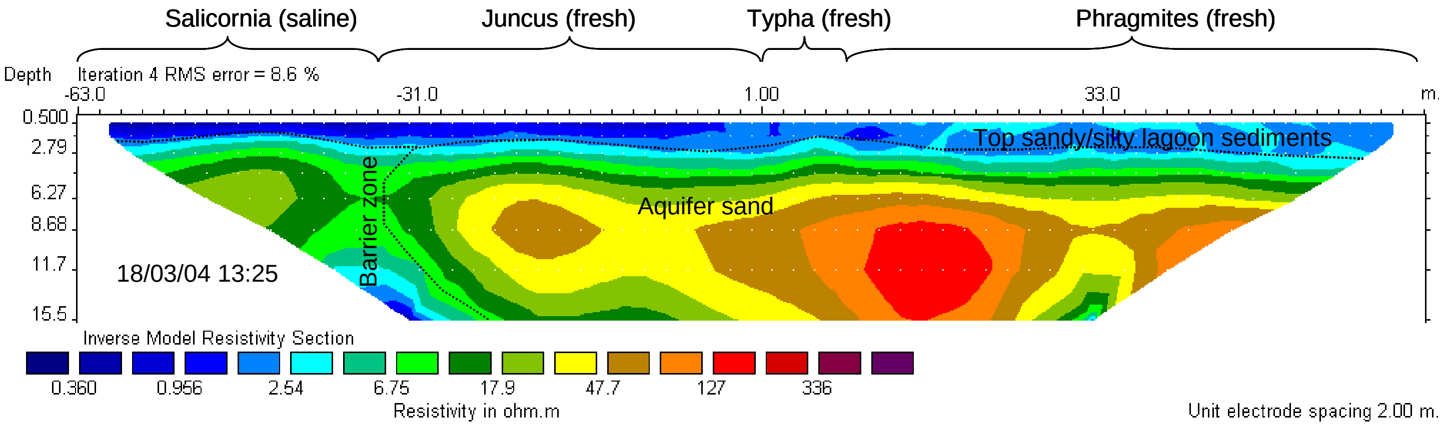

Figure 3.9: Results of multi-electrode resistivity geophysical investigation across the boundary of the aquifer-fed low salinity *Phragmites* reed beds and the salt marsh characterized by *Salicornia.* The higher resistivity (100 – 300 ohm.m) areas below the *Phragmites* at 6 to 15 mbgl may indicate fresher groundwater discharging towards the shallow, mixing zone within rooting depth.

4. IDENTIFYING ADES IN SOUTH AFRICA

Historically, ADEs were identified as they wilted and died as a result of groundwater abstraction. Nowadays we are attempting to identify and understand ADEs in order to protect them and the aquifer attributes on which they depend. Identification and verification of ecosystem groundwater use and dependency generally requires a multidisciplinary approach. Identifying ADEs requires knowledge of the catchment water balance with a more complete understanding of the role of aquifers.

The first important step is conceptualising groundwater contact with the surface environment and looking for contrasting ecosystems which occur in areas or situations where there is likely to be groundwater available. For example, an area with shallower groundwater in flood plain alluvium deposits may have taller trees and riparian species. Or a river may become perennial downstream of a fault zone, due to groundwater-fed baseflow, with an aquatic ecosystem which relies on permanent flow.

The sections below give an overview of some of the methods to assess whether terrestrial and aquatic ecosystems are linked to aquifers. Essentially the following questions need to be answered within any given catchment:

- Where could aquifers be linked or discharging to the surface environment?
- Do we see ecosystems which are different in these areas and appear to rely on a higher water budget which includes groundwater?
- How can aquifer dependency be verified at a field scale?

From this point, the catchment manager needs to decide the level of detail necessary to characterise the link between the aquifer and the ecosystem. This will usually depend on the importance of the ecosystem; threats to the groundwater required by the ecosystem; other risks posed to the ecosystem; the feasibility of implementing protection measures. Often an investigation involving a hydrogeologist and a botanist or aquatic ecologist is required.

4.1 IDENTIFYING VEGETATION LINKED TO AQUIFERS

Many tools are available in South Africa to identify ADEs. The figure below shows the applicability of various tools for terrestrial, riparian and wetland habitat types at different scales (Figure 4.1). At a catchment scale it is useful to start with large scale remote sensing spatial datasets to identify relatively lush vegetation and correlate these to aquifer discharge areas.

In addition to these tools, spatial groundwater and ecological datasets and expert hydrogeological and ecological knowledge are essential to identifying ADEs. Generally neither one alone is sufficient and multiple scales of assessment are required. Groundwater data is often a limiting factor in developing countries. Expert knowledge may assist in describing conceptual aquifer models based on known geology and inferring flow regimes and probable discharge areas. The protocol shown in Figure 5.2 assists catchment managers in identifying terrestrial groundwater dependent ecosystems and the need for protective RQOs (discussed in the following section).

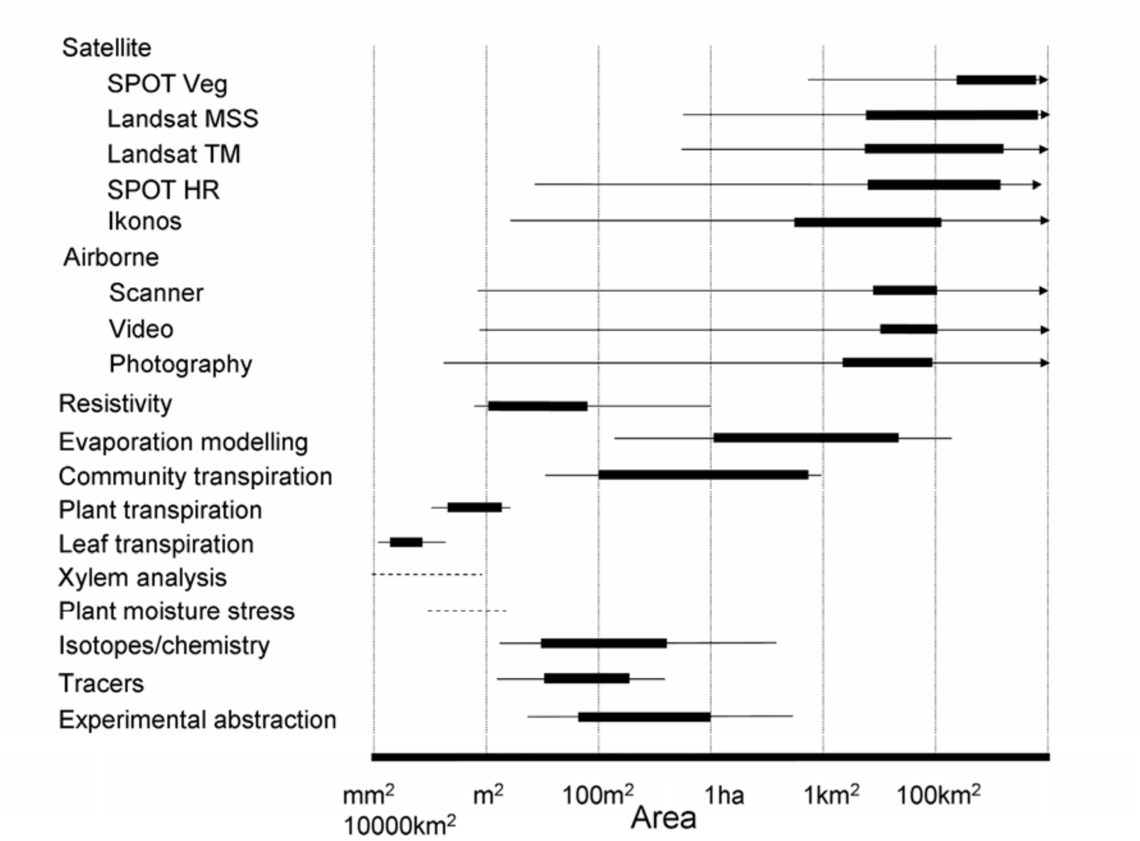

Figure 4.1: Tools to identify groundwater dependent vegetation at different scales in South Africa (Colvin *et al.*, 2003a).

4.2 *QUANTIFYING FLOW BETWEEN GROUNDWATER AND SURFACE WATER*

Numerical flow models offer the best means of quantifying the flow between groundwater and surface water. Such models however, are dependent on accurate water level measurements (aquifer and surface water body) and time-series data (streamflow and groundwater level) to enable calibration. Use of this approach in South Africa is in most catchments constrained by poor understanding of aquifer characteristics and a lack of groundwater level and river stage height data. Calculations of flow between surface water and groundwater could be quantified by using Darcy’s Law. A summary of how such calculations are made is presented by Parsons (2003). Input parameters include vertical hydraulic conductivity of the surface water body base and its thickness, the size of the area over which the interaction occurs, groundwater elevation, surface water elevation, and aquifer transmissivity and average groundwater hydraulic gradient. Often limited data are available on the hydraulic conductance of the stream bed.

The availability of streamflow data has enabled the application of graphical hydrograph separation techniques to define the baseflow component for most South African catchments. The separation of stream flow into its different components through hydrograph separation offers hydrogeologists insight into the processes by which water drains through catchments. Hydrograph separation is based on the premise that the components of surface water flow arrive at different intervals. Two components are typically assigned to streamflow; the quickflow component, which is equated to overland flow; and the low flow components, which are derived from saturated groundwater and interflow discharge (Saayman *et al.*, 2003). Lerner (1996) highlights three baseflow separation approaches as useful to water resources management (Table 4.1). Preliminary indications are that infiltration rates in undisturbed soils are high and most river flows, even the quick flows are actually from sub-surface flows rather than overland flow.

Table 4.1: Three useful approaches to baseflow separation (after Lerner, 1996):

	Approach	*Disadvantages*	*Advantages*
Graphical Separation	A hand-drawn separation is made of daily flow plots. One approach is proposed by Hewlett and Hibbert (1967) in which quick-flow is separated from delayed flow by a line of constant slope (0.0472 mm/day).	Produces inconsistent results between years and between hydrologists. No allowance is made for the inter-flow component.	Is a quick and relatively easy method to apply. Recent advances allow computer based separation. Requires streamflow data only.
Baseflow Rating Curves	Flows during the dry season are correlated with groundwater levels in a representative observation well, to generate a rating curve. During the wet season the curve is used in reverse, with field observations of groundwater levels used to estimate baseflow.	The method requires the collection of streamflow and groundwater level records. No allowance is made for the inter-flow component.	Results integrate streamflow and groundwater information.
Recession-curve displacement	An automated procedure that estimates baseflow by studying the displacement of the hydrograph during each event. It is a graphical analysis of the hydrograph.	There is no theoretical justification for claiming that it estimates groundwater discharge.	Allows for the easy analysis of long-term streamflow records. No data other than streamflow is required for analysis.

Understanding the contribution of groundwater to streamflow is an important component of groundwater Reserve determinations. In this process it is important to include an identification of the interflow component, in addition to stormflow and aquifer-fed baseflow (Parsons, 2003) rightly points out that any technique that separates streamflow into only stormflow and baseflow is flawed, in that it ignores the interflow component. Interflow occurs independent of the aquifer groundwater component, and therefore cannot be affected by groundwater abstraction. Hydrograph separation techniques must therefore be modified to reflect only the saturated groundwater discharge if they are to contribute to management decisions.

4.3 ASSESSING ADES AT A NATIONAL SCALE

It is not possible to indicate the actual location of ADEs at a national scale, due to scientific uncertainty about aquifer discharge areas and the scale of ADE occurrence. However, we can indicate probabilities of ADEs occurring and give an indication of which types may occur given our broad understanding of the aquifers (Figure 2.3) and the types of ecosystems which are linked to them in different parts of the country. We can also use available datasets on groundwater to indicate aquifer vulnerability to disruption of aquifer flow regimes and discharge rates, and abstraction and land-use data to indicate potential hazards to the quantity and quality of aquifer discharge to ecosystems. This enables us, at a coarse national scale, to start identifying which areas are most at risk.

The national Groundwater Resource Assessment (GRA) project has provided datasets on key characteristics of groundwater resources, including ground water level depth, storage, recharge, vulnerability to contamination and consumptive use (DWAF GRA, 2005). The aim of the GRA was to try and provide a first national scale assessment of the groundwater resource and the results must be interpreted with care. They are based on extrapolation from very limited and, often, poor quality data but they are the best information available at a national scale at present. The information that is of relevance to managers of groundwater resources is described and interpreted below.

The availability of groundwater close to the surface is the most important prerequisite for ADEs. Figure 4.2 shows the estimated groundwater levels at a national scale. Where groundwater occurs within 5m of the surface (or at <5 m below ground level) there is a high probability of ecosystems connection. At greater than 10m the water table will be out of the reach of most non-woody plants, excluding deep rooting species such as Camelthorn, Acacia karoo, *Boscia albitrunca* and *Olea suropaea* subsp. africana in the semi-arid areas.

There is low confidence in this data because groundwater may appear at more than one level beneath the surface and there is often substantial variation between adjacent boreholes. At a local scale it is more important to have a good understanding of aquifer flow regimes as depicted in a cross section of the Table Mountain Group Aquifer in the Cape Mountains (Figure 4.3). In this situation, recharge from the relatively high rainfall in the mountain areas flows through the fracture systems and fault zones in the sandstones to emerge at springs on geological contacts, often a considerable distance from the recharge zone. However, the national groundwater level data is useful for this overview.

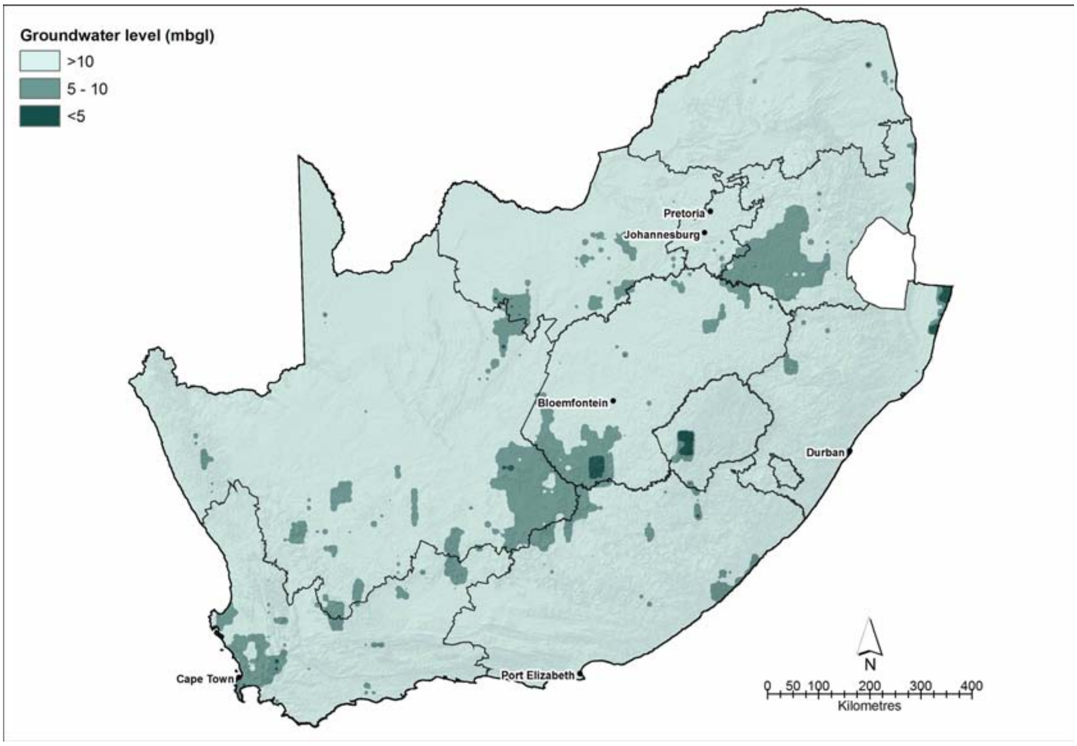

Figure 4.2: Groundwater levels at a national scale in South Africa (Source data: GRA project, 2005).

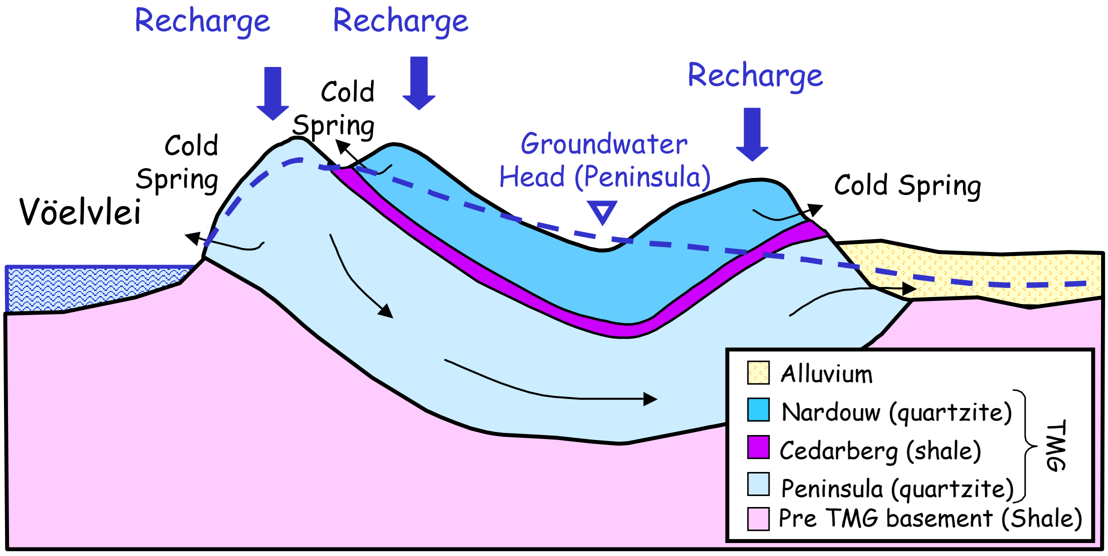

Figure 4.3: Cross-section of aquifer flow in the Table Mountain Group Aquifer. Precipitation and topographic gradients drive longer flow paths in the Peninsula. Discharge to springs and alluvium. Flow paths in Nardouw are perpendicular to the cross-section (Source: WRC, 2003).

Risks to Aquifer Dependent Ecosystems.

This section presents a national scale assessment of risks to ADEs. The resultant overview is intended to guide catchment managers and those using groundwater by indicating where ADEs may need protection. The risk assessment takes into account:

- the intrinsic vulnerability of aquifers to disturbance of discharge regimes based on water levels, recharge and storage;
- hazards posed to aquifer flow regimes and quality in terms of groundwater abstraction rates relative to recharge and polluting land-uses.

Shallow groundwater levels, shown in figure 4.2, indicate aquifer discharge areas. Flow through the aquifer is controlled by climate, principally precipitation which results in recharge to the aquifer, and the geology of the aquifer, which determines the permeability and storage of water underground. Figure 4.4 shows calculated variations in aquifer storage (both fracture zone and weathered zone storage) from the GRA national dataset. Figure 4.5 shows calculated mean annual aquifer recharge based on the chloride method calibrated against baseflow calculations (DWAF GRA, 2005).

Areas with high storage and high recharge will be more resilient to groundwater abstraction and disturbance to the flow regime. Table 4.1 shows vulnerability ratings based on water levels, storage and recharge. Each aquifer is scored on all three characteristics and the sum of the three scores determines the vulnerability. Thus an aquifer type which scores 3 (i.e. high) for all three characteristics gets a vulnerability score of 9.

Table 4.1: Calculation of aquifer vulnerability to disturbance of discharge regimes based on groundwater levels, storage and recharge.

Vulnerability rating and score	*Aquifer Storage (mm)*	*Aquifer Recharge (mm)*	*Groundwater levels (mbgl*)*
High (3)	< 125	<30	0-5
Medium (2)	125-500	30-60	5-10
Low (1)	>500	>60	>10

**mbgl – metres below ground level*

An overall assessment of vulnerability (or sensitivity) of aquifers to disruption of aquifer discharge to the surface environment is given in Figure 4.6. This is based on spatial data from the national groundwater archive (NGA) or calculated and interpolated from the GRA project. The map (Figure 4.6) shows the least vulnerable aquifers to be in the high storage, moderate recharge areas of Gauteng where groundwater levels are typically greater than 10m. The Karoo dykes and sills and fractured meta-sediments are highly vulnerable due to low storativity, low recharge and moderate to shallow groundwater levels.

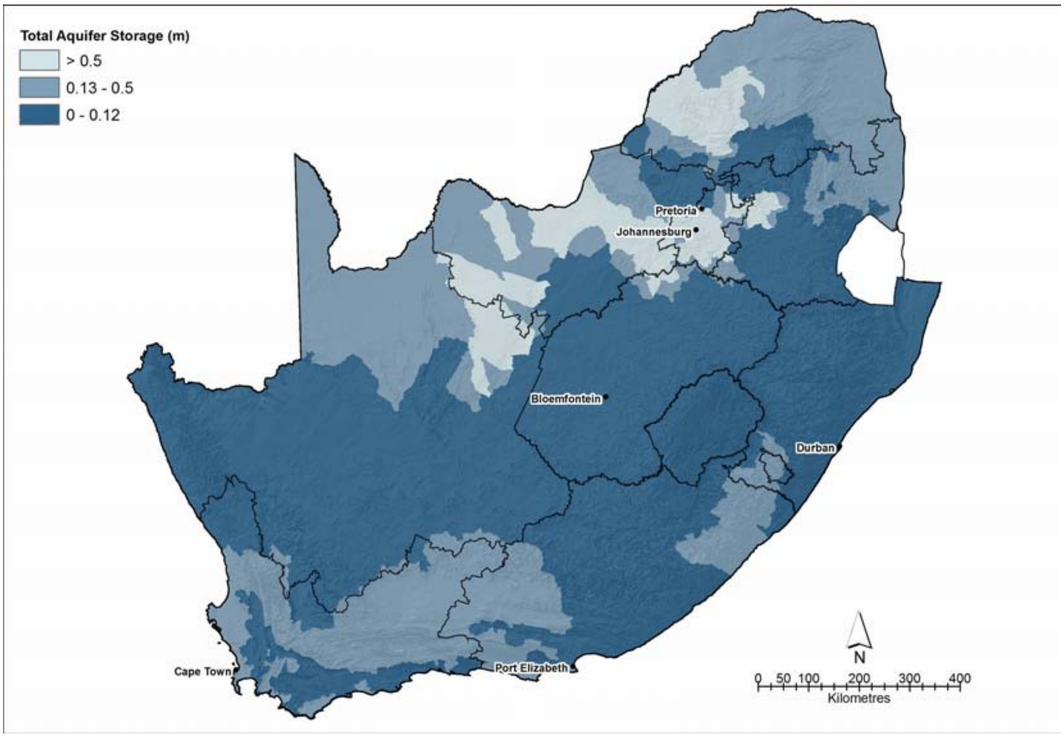

Figure 4.4: Total Aquifer Storage at a National Scale. (Source data: GRA project, 2005)

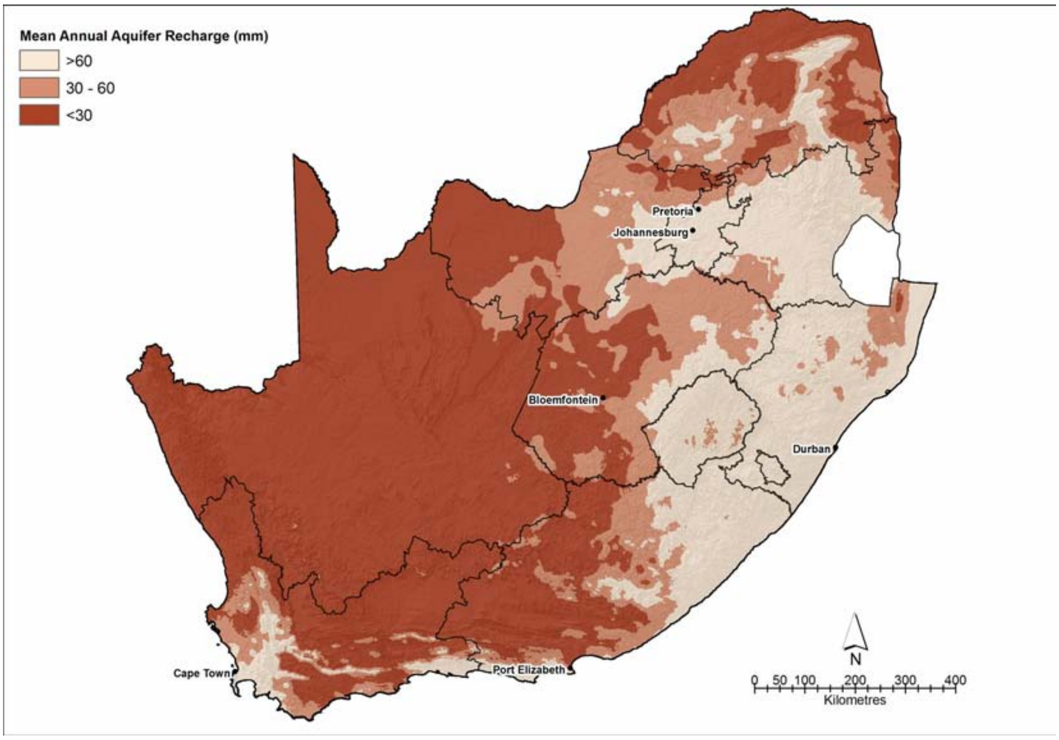

Figure 4.5: Mean annual aquifer recharge at a National Scale. (Source data: GRA project, 2005)

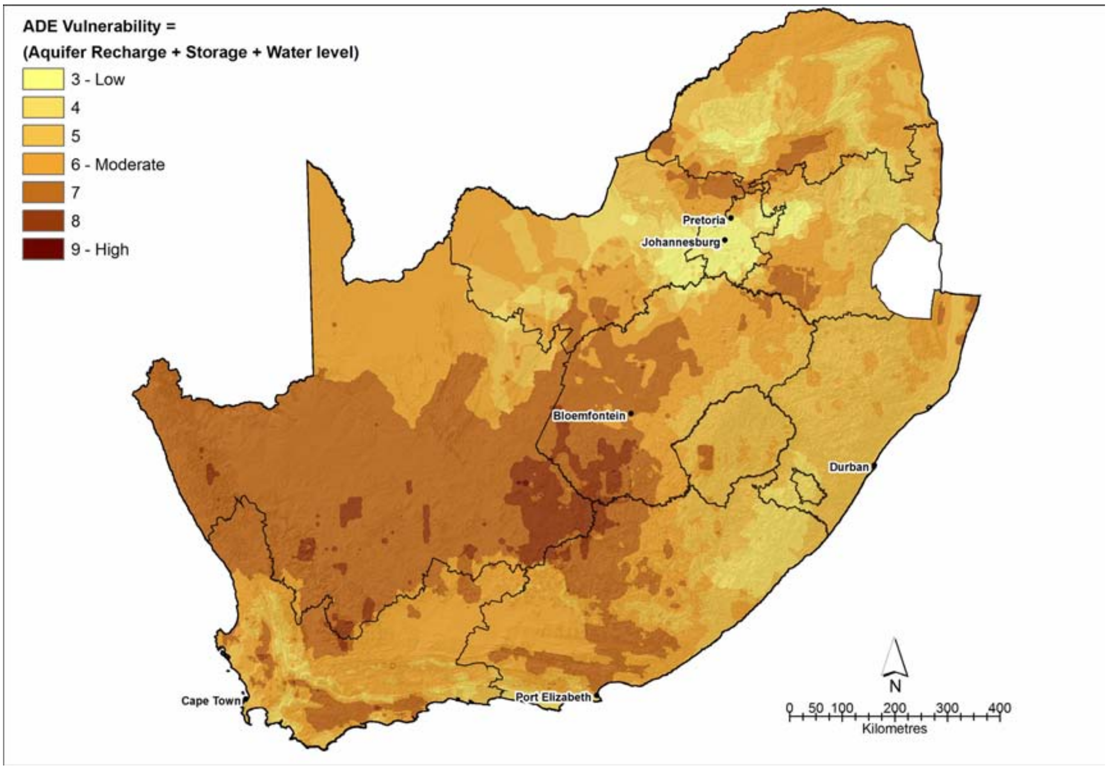

Figure 4.6: Aquifer vulnerability to disturbance of flow regimes supporting ADEs; based on groundwater level, total aquifer storage and mean annual recharge. (Source data: GRA project, 2005)

Hazards to aquifer discharge areas and flow regimes are posed by groundwater abstraction and changing land-cover, which disrupts the local hydrogeologic systems. An assessment of available groundwater abstraction figures (DWAF GRA, 2005), compared to recharge estimates indicates where abstraction is approaching sustainable limits in terms of volumes (Figure 4.7). Limited ground-truthing of the national scale abstraction figures indicates that they are likely to be an underestimate and the proportion of the recharge which is used is likely to be higher than is shown here (DWAF, GRA, 2005).

The national land-cover data set (NLC) was used to define categories of risk to aquifer flow regimes. For example, mining is a high hazard activity as is permanently irrigated agriculture. Urban development is medium hazard and other agriculture is low hazard. The distribution of these hazards is shown in Figure 4.8. The full classification of NLC types into different levels of hazards is presented in Appendix D of the accompanying WRC report.

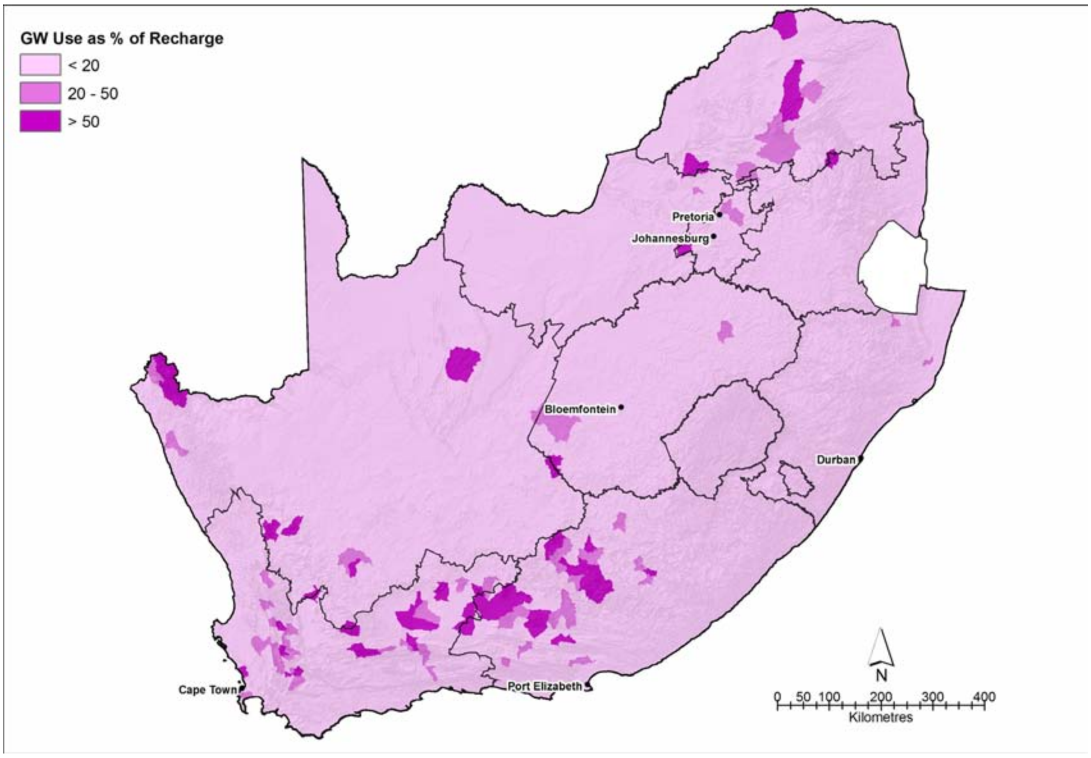

Figure 4.7: Groundwater abstraction volumes as a percentage of mean annual recharge per quaternary catchment. (Source data: GRA project, 2005)

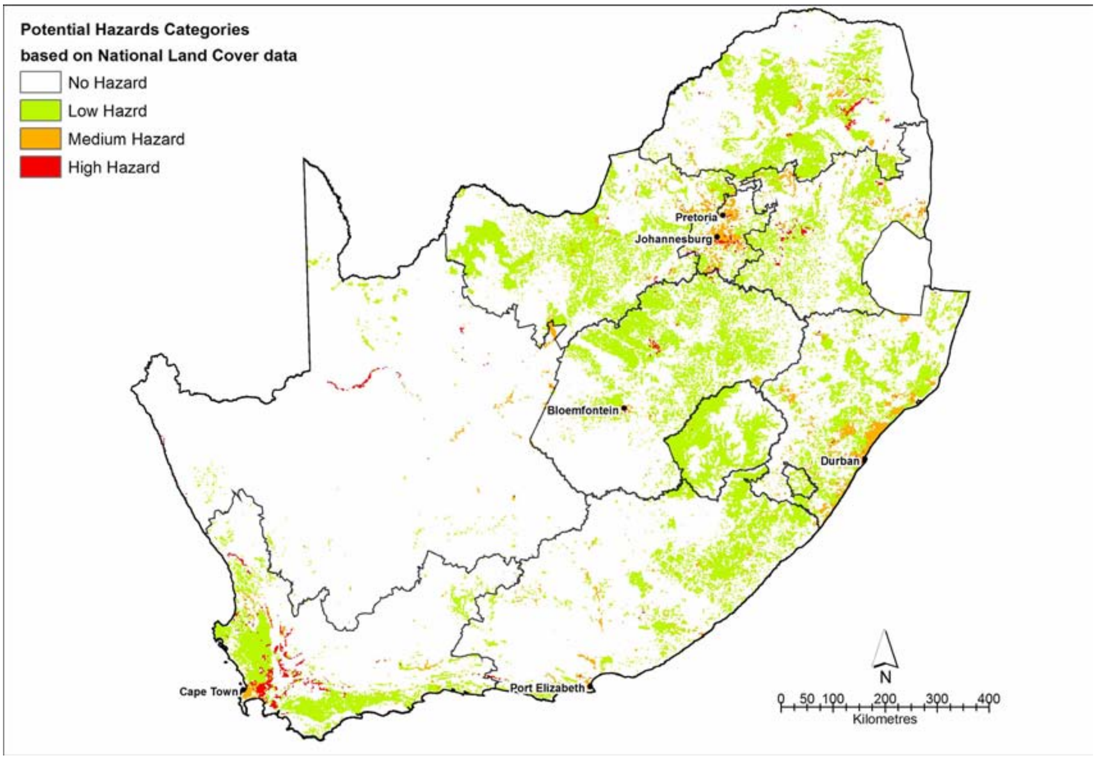

Figure 4.8: Land-cover as an indicator of hazards to aquifer flow regimes supporting ADEs. (Source data: National Land-Cover, 2005)

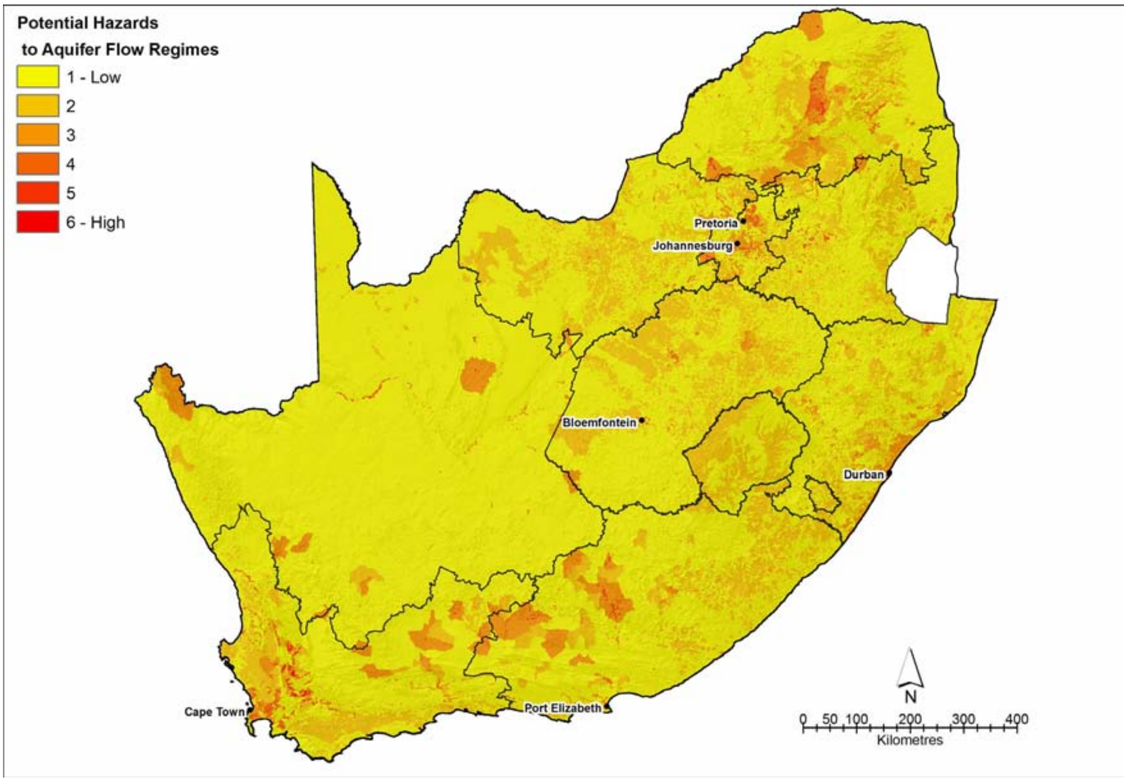

Figure 4.9: Combined potential hazards to ADEs based on groundwater abstraction and land-cover. (Figures 4.8 and 4.9)

The two principal hazards (abstraction and land-cover) are combined to show a total hazard in Figure 4.9. Quaternary catchments with high levels of groundwater abstraction come out strongly.

Risk is a combination of vulnerability and hazard. The total current risk to ADEs due to disturbed groundwater discharge regimes is presented in Figure 4.10. Although the Karoo area is highly vulnerable, it has a low total risk due to the absence of hazards. However, the high levels of use in the Klein Karoo make this a high risk area.

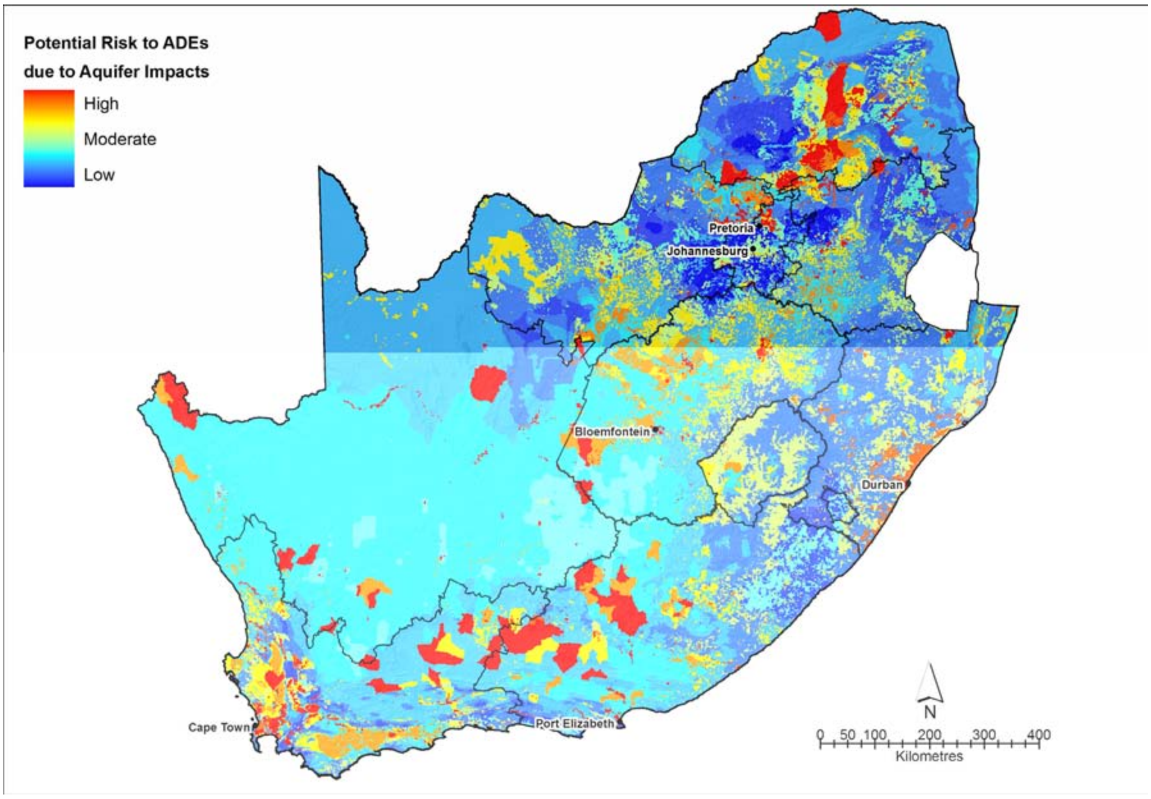

Figure 4.10: Potential risk to ADEs based on an assessment of aquifer vulnerability and presence of hazards at a national scale. (Figures 4.7 and 4.10).

5. SUSTAINABLE MANAGEMENT OF GROUNDWATER AND ADES

South Africa is a water-scarce country and it is believed that current levels of consumptive use may be close to sustainable limits. Statistics on water use, and in particular groundwater use, are poor. It is estimated that groundwater supplies 15% of bulk water supply, around 10% of agriculture and over 50% of rural communities supplies. Prior to the 1998 water law, groundwater had a variable status which differed from surface water and it could be deemed a private resource.

5.1 PRINCIPLES OF SUSTAINABLE WATER MANAGEMENT

Under the National Water Act (Act 36 of 1998), groundwater has the same status as surface water, and may not be privately owned. The Act explicitly recognizes the following principles of integrated water resource management:

- Water is a *scarce* and *unevenly distributed* national resource which occurs in many different forms, all of which are interdependent and part of the water cycle;
- Water is a natural resource that *belongs to all people*, however, the discriminatory laws and practices of the past have prevented equal access to water, and use of water resources;
- The National Government should ensure the *equitable allocation* of water *for beneficial* use, including the redistribution of water;
- The government should take account of *international water* matters;
- The *protection of the quality* of water resources is necessary to ensure *sustainability* of the nation's water resources in the interests of all water users;
- The management of water resources should *integrate* all aspects of water resources and, where appropriate, should be *delegated* to a regional or catchment level so as to enable everyone to *participate*;
- Every person has the right of access to basic water supply and basic sanitation necessary to ensure *sufficient water* and an *environment not harmful to health* or well-being.
- The National Government is the *custodian* of the nation's water resources

The recognition of the connection of groundwater to surface water and the requirement for sustainable use are of particular importance for the future management of ADEs in South Africa.

5.2 POLICIES AND LEGISLATION RELEVANT TO ADES IN SOUTH AFRICA

South Africa has ratified a number of international agreements which are relevant to the protection of ADEs, including the Convention on Biological Diversity (CBD), the Convention on Migratory Species (CMS), and the Convention on Wetlands especially as Waterfowl Habitats (Ramsar).

The South African constitution includes a basic human right which requires the environment to be protected from degradation to sustain human health, well-being and secure sustainable development. This right has been reflected in the provisions of water for ecosystems and basic human needs in the Water Principles (above), enacted in the National Water Act (NWA); the Environmental Management Policy (EMP), enacted in the National Environmental Management Act (NEMA); and in the White Paper on the Conservation and Sustainable Use of South Africa's Biodiversity, enacted in the National Biodiversity Act (NBA). Management of all environmental aspects of water resources therefore fall within the domain of policies on both water resources and environmental management.

The National Water Act and the Resource Directed Measures

The Resource Directed Measures (RDM) are measures contained in the National Water Act and are intended to protect water resources to ensure sustainable use. They include:

- **classification,** which indicates the level of impact acceptable for a particular water resource;
- the **Resource Quality Objectives**, which describe particular attributes of the water resource to be maintained;
- and the **Reserve**, which describes the quantity and quality of water required for aquatic ecosystems and basic human needs.

The Catchment Management Agencies (CMAs) and the national Department of Water Affairs, in consultation with stakeholders, will develop and describe a vision for water resource development in an area. This will describe what the available water should be used for, how much impact is acceptable, how the ecosystems linked to rivers and aquifers should be managed and what aspects of the resource should be protected and monitored. All significant water resources in an area need to be identified, quantified and classified according to how much impact is acceptable. The Groundwater Resource Directed Measures (GRDM) manual (DWAF, 2004) provides detailed guidelines on the approach and outcomes of the RDM process. The quantification of the resource will include an assessment of its present state, or current degree of impact. The management class will indicate the desired future state for the resource and the catchment management strategy will need to outline how this can be achieved through licence conditions, allocation strategies, changed land-use and waste water management. The process of deciding the management class needs to take account of the costs and benefits of changing the status quo. ADEs will provide a critical end-point for sustainable aquifer management.

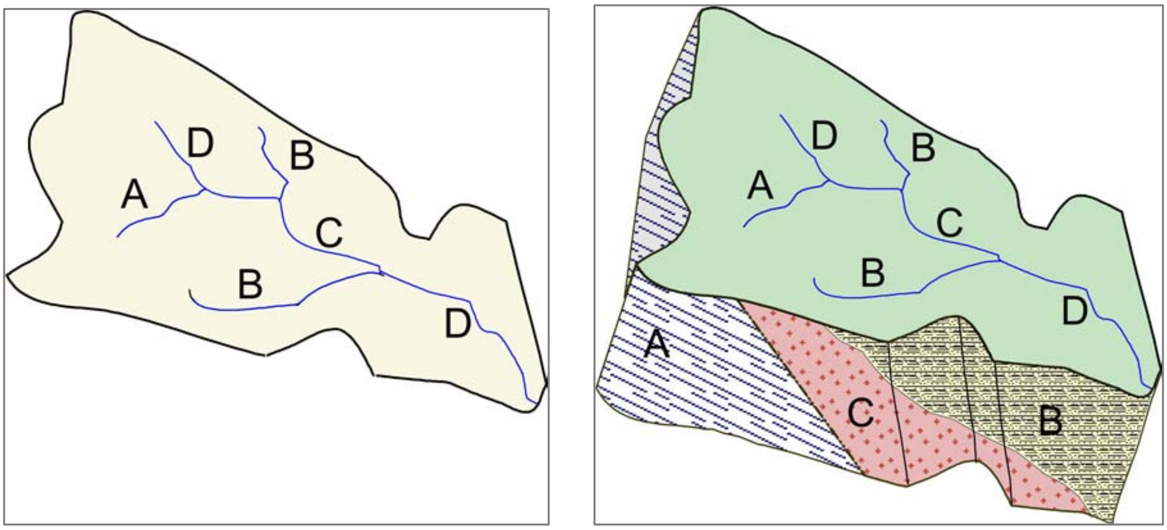

Figure 5.1: A schematic representation of Classes of water resources in a catchment (A – pristine; B- lightly impacted; C - moderately impacted; D – heavily impacted within sustainable limits). (Source: DWAF, GRA Classification, 2005)

It is envisaged that different tributaries or reaches of the main stem of a river will be given different classes depending on the level of required use and ecosystem protection, as shown in Figure 5.1. The configuration of classes within the catchment should ensure that the estuary does not fall below a D-class (heavily impacted within sustainable limits). Similarly aquifers will be classified to optimise the sustainable use of groundwater (also Figure 5.1). Areas or nodes of interaction with surface water and the surface environment will be critical in determining the level of acceptable impact on the aquifer as a whole. Careful management and siting of abstraction wells will be needed to maintain high levels of environmental functioning from aquifers. Discharge areas which support springs, wetlands and baseflow require the maintenance of high water levels and near natural flow regimes. Terrestrial, coastal and riparian systems are sensitive to rapid declines in the water table and abstraction should be planned, managed and monitored to ensure it occurs within sustainable limits.

The RQOs are thought to be a particularly powerful legal instrument to protect ADEs. The Reserve is intended to protect and maintain the resource base, including biotic components, to ensure the sustainability of surface water resources. ADE wetlands, rivers and springs, may be afforded the high priority protection of the Reserve. RQOs are not restricted to aquatic ecosystems, as described below, and may be used to protect terrestrial ADEs. The full ecological role of groundwater may be recognised and protected where necessary.

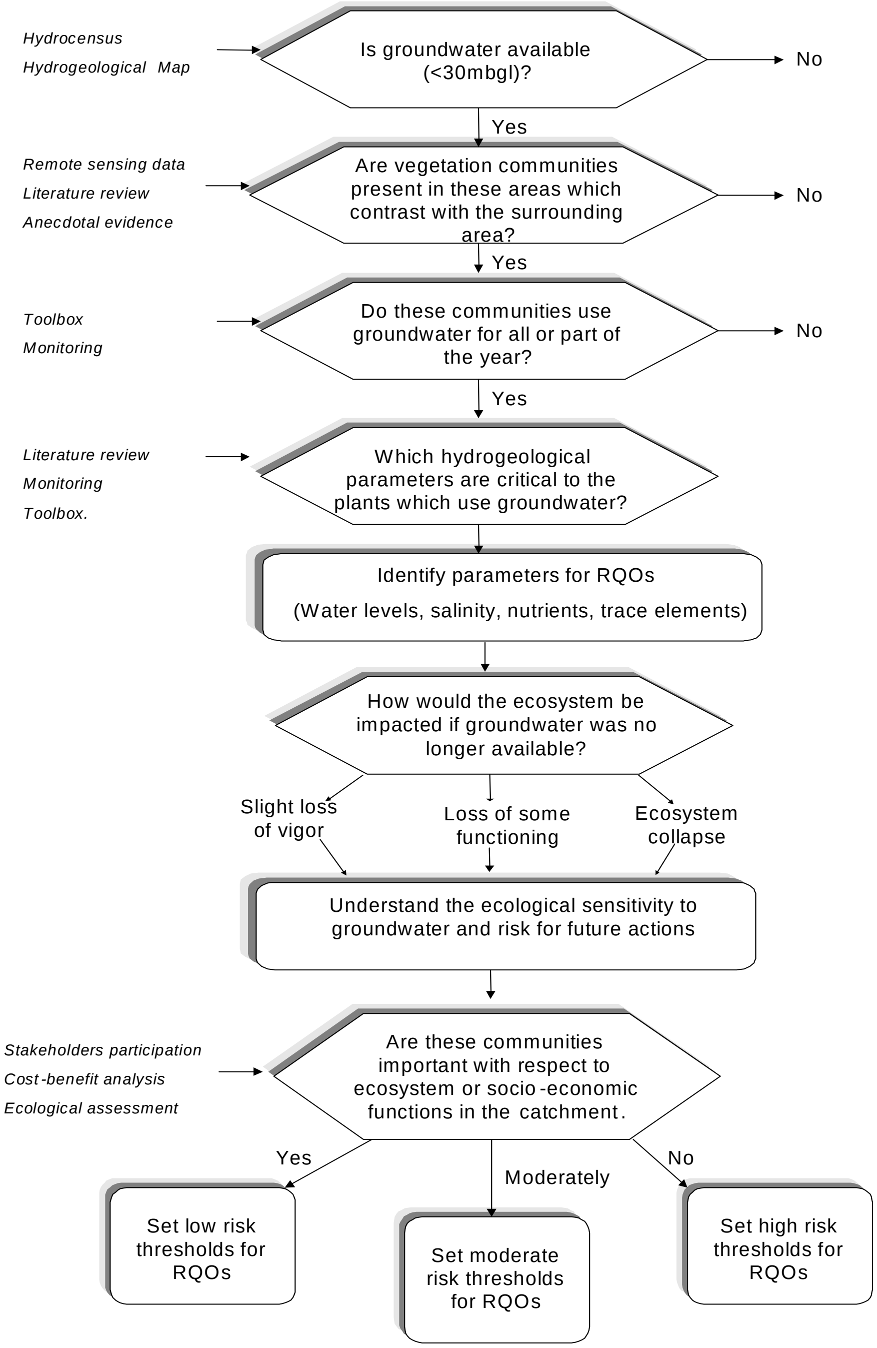

Figure 5.2: A protocol to identify terrestrial ADEs in South Africa (Colvin et al., 2003a). A "no" indicates that groundwater is unlikely to be a significant factor in the ecosystem being assessed.

For both RQOs and the Reserve, the level of impact allowed can vary depending on how the aquifer is classified by stakeholders and it is not expected that pristine, or reference conditions, will be chosen for many aquifers. The NWA states *'that the purpose of the resource quality objectives is to establish clear goals relating to the quality of the relevant water resources. In determining resource quality objectives a balance must be sought between the need* ***to protect*** *and sustain water resources on the one hand, and the need* ***to develop and use*** *them on the other. ..'*

Resource Quality Objective (RQOs) may relate to (NWA, 1998): The Reserve; instream flow; water levels; the presence and concentrations of particular substances in the water; the characteristics and quality of the water resource and the instream habitat 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 the quality of the resource; any other characteristic of the water resource in question.

RQOs may be seen as goals to aim for, or thresholds or safety nets which represent the limit of acceptable impact. They may be numeric or descriptive. RQOs for groundwater could include:

- Water levels, groundwater gradients, storage volumes, a proportion of the sustainable yield of an aquifer and quality parameters required to sustain groundwater component of Reserves for basic human needs and baseflow to springs, wetlands, rivers and estuaries.
- Groundwater gradients and levels required to maintain the integrity of the aquifer and the aquifer's broader functions.
- The water table or piezometric levels.
- The presence (or not) of dissolved and suspended substances (naturally occurring hydrogeochemicals and contaminants).
- Aquifer parameters such as permeability, storativity and recharge; landscape features such as springs, sinkholes and caverns characteristic of the aquifer type; subsurface and surface ecosystems in which groundwater fulfils any vital function; bank storage and storage with alluvial aquifers which support riparian vegetation.
- Aquatic biota in features dependent on groundwater baseflow, such as rivers, wetlands, and caves, or biota living in the aquifer itself or the hyporheic zone. Terrestrial plants and ecosystems dependent on groundwater.
- Land-use and water use which impact recharge quantity or quality. Subterranean activities, such as mining or waste disposal, which impact the aquifer directly. [This would exclude activities which impact or occur solely in aquitards.] The control of land-based activities by aquifer protection zoning of land-use.
- Any other groundwater characteristic.

Over 130 groundwater Reserve determinations have been carried out for DWAF (2000 – 2005). These are described in terms of the volume and (sometimes) quality of groundwater required to meet the needs of aquatic systems. The result of the groundwater quantification process which is currently embedded in the GRDM is typically a low-confidence estimate of average annual recharge rates, the volumes that are discharged to surface water and the volumes that remain in the aquifer and may be allocated. Many of these have yet to be tested and a higher confidence, precautionary approach can be linked to RQOs which specify water levels and flow system gradients to be maintained in buffer zones close to discharge areas.

National Environmental Management Act and Environmental Impact Assessment

NEMA recognises that environmental matters are shared between the national and provincial governments, including the responsibility for dealing with Environmental Impact Assessments (EIA). The basic requirement for EIAs will be the preparation of a preliminary scoping document to determine whether there are ecologically sensitive features associated with the water resource, including ADEs.

The purpose of an Environmental Impact Assessment (EIA) is to provide decision-makers with adequate and appropriate information about the potential positive and negative impacts of a proposed development. Where a development could or will impact on groundwater or an aquifer linked system, specialist hydrogeological input is usually required. In most instances such input will address the baseline characteristics of the system, responses to key issues and concerns, comparisons of alternative approaches, recommendations for management actions and for monitoring programmes. Guidelines are available on the need for specialist hydrogeological input to EIAs (Saayman, 2005).

Specialist hydrogeological input will be required where:

- Abstraction occurs from an aquifer that sustains or contributes to river baseflow or any other surface water feature where it is likely to contribute to ecosystem functioning.

- A wetland or sensitive ecological setting that is probably sustained by groundwater occurs within the area of influence of the proposed development. This area of influence will vary, depending on the hydrogeological setting and the nature of the development. It is suggested that a radius of 1 kilometre be used as an initial guideline of whether such ecosystems occur near the proposed development.

Of particular relevance to assessing impact on ecosystems is the time and space boundary assigned to the study. Decisions on this will be a function of factors such as the scale of impact associated with the development and the value and sensitivity of the groundwater resource, groundwater dependent ecosystems and the discharge environment. Factors to consider when defining the time and space boundary of the input are:

- The aquifer flow regime and boundary effects.
- Seasonal variation and dependence.
- The ecological status, value and complexity of the receiving environment.
- The area over which a change in water quality or water levels could occur.
- The need to assess users and uses of the aquifer and/or the impacted environment.

As part of hydrogeological input, possible environmental and operating scenarios that could influence the nature, extent, duration, magnitude/intensity, probability and significance of anticipated impacts should be assessed. It should also be considered that groundwater is particularly susceptible to the cumulative effect of small impacts. During the EIA due regard must be given to this. Where RQOs exist, the impact of the proposed development on these should be discussed within the context of its contribution to the cumulative effect.

Once the groundwater receiving environment has been identified, the EIA must determine the effect of the development in terms of beneficiaries and losers. Inevitably trade-offs are made in decision-making and the assessment must, therefore, inform this process. Important in this regard are criteria such as societal value, vulnerability, relative importance, equity and fairness.

5.3 DO WE KNOW ENOUGH TO MANAGE AND PROTECT ADEs?

Groundwater - surface water and groundwater- ecosystem interactions happen at various scales and may be seasonally interchangeable. The hydrological complexity of this relationship presents a problem for the integration of ecohydrology and water resources management.

Often catchment managers need to know how much water is needed for a river and how much is available for allocation. Approximate water balance figures are required with an understanding of assurance of supply and the cost of abstraction. However, the impacts of abstraction on ADEs are often difficult to predict. Inflows of water to a catchment, in terms of rainfall, are always variable and unpredictable so available surface and groundwater cannot be known with a high degree of certainty and this makes management planning difficult. Further difficulties in protecting ADEs result from our incomplete understanding of aquifer systems and how they will respond to abstraction. ADEs are often dependent on the ‘overspill’ or highest groundwater levels, and essentially rely on the aquifer being ‘full’ in certain places and at certain times of the year.

Setting these water levels are targets for protection (or RQOs) and issuing licenses to abstract groundwater contingent on these targets being met is one way of circumventing our incomplete understanding and knowledge. It requires **adaptive resource management** (ARM) on the part of the water managers and users (Rogers, 2002). ARM relies on monitoring, and the capacity and flexibility to respond to changing resource conditions. In under-capacitated, developing countries, such as South Africa, this presents a challenge, however the adaptive approach of 'learning by doing' also provides a means to use groundwater with an insufficient knowledge base.

Continued research is required to answer some of the key questions about ADEs that will enable better management. These include:

- How do deep tap roots 'know' where the water table is and how quickly can they track it?
- Is high nitrate in groundwater important for plants?
- How much water is transpired from the water table at different times of the year?
- How does access to aquifers influence soil moisture in arid and semi-arid areas?
- How does groundwater flow between the active channel, bank storage, permanent pools and riparian trees in non-perennial rivers?
- How does stream bed conductance limit connections between surface water and groundwater, and how much does this vary within and between river reaches?
- Are there natural tracers that can be used to quantify aquifer discharge to aquatic systems?
- What is the range in values aquifers-rivers interactions determined by numerical models and analytical models at a catchment scale?
- What is the most relevant scale to assess groundwater – surface water interactions?
- What are the critical data required for this scale of interaction?

6. CONCLUSIONS

Aquifer Dependent Ecosystems (ADEs) occur throughout the South African landscape in areas where aquifer flows and discharge influence ecological patterns and processes. They are ecosystems which require groundwater from aquifers for all or part of their life-cycle to maintain a habitat with a water budget, or water quality, which contrasts with the surrounding ecosystems.

The multiplicity of types and scales of ADEs can be simplified into type-settings based on 8 principal aquifer types (based on lithology) and 7 habitat types. The type-settings describe the supporting aquifer type and ecosystem or habitat setting. Examples of known South African ADEs include: in-aquifer ecosystems in the dolomites (North West Province); springs and seeps in the TMG sandstone (Western Cape); terrestrial keystone species such as *Acacia erioloba* in the Kalahari; lakes and punctuated estuaries on the shallow sand aquifers of the east coast in KwaZulu-Natal; riparian zones in the seasonal alluvial systems of the Limpopo; seeps on the Karoo dolerite sills.

The identification of ADEs is often difficult but needs to be focused initially at a catchment scale, which is most relevant for water management and allocation. Proving links between ADEs and aquifers often requires detailed, multi-disciplinary observation and assessment. At a coarse national scale we can identify areas with a high probability of supporting terrestrial and aquatic ADEs. We can also assess aquifer vulnerability to disturbance of discharge regimes and potential hazards to ADEs to give a national scale ADE risk map. Both ADE occurrence and risk should be verified at a local scale, but the overview guides preliminary decision making about ecosystem protection and groundwater potential for abstraction.

South Africa is moving towards IWRM, enabled by new legislation and a transforming water sector. ADEs are beginning to be considered in the context of IWRM and provide an ecological boundary for sustainable groundwater use. Legislation exists within NEMA and the NWA to protect ADEs. A proposal to impact or develop a groundwater water resource should be subject to three tests: whether it impacts the requirements of the ecological Reserve, whether it impacts the Resource Quality Objectives (RQOs), and whether environmental standards and goals under NEMA are affected. These measures should safeguard the conservation and ecological requirements of ADEs if fully implemented.

Successful protection of ADEs will require cooperative governance of land, water and the environment. The main custodians are DEAT and DWAF but management needs to happen at the grass-roots level of farmers, mines and municipalities who manage aquifers on a day-to-day basis. It will be important to raise the public’s awareness of the role aquifers play in sustaining the surface environment.

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8. GLOSSARY

Abiotic - the non-living (bios = Greek for life) environment such as rock, water molecules, climatic conditions (McGraw-Hill, 1978).

***Actual evaporation* -** the amount of *water evaporated* under a given set of circumstances where water supply or other factors limit evaporation (Ward, 1975) (as opposed to potential evaporation which is evaporation under non-limiting circumstances, as from an evaporation pan). Symbol AET or Aet or E_a.

Aeolian - driven or caused by the action (movement) of the wind; thus aeolian deposits are of wind blown material, for example sand-dunes (McGraw-Hill, 1978).

Aerobic - a process such as a reaction taking place in, or requiring the presence of, oxygen; also used in the sense of oxygen requiring as in aerobic bacteria (Chambers, 1996).

***Alluvial* -** used to describe material (e.g. sediments) deposited by flowing water (McGraw-Hill, 1978).

Alluvial aquifer - an aquifer formed of unconsolidated sediments deposited by flowing water (river or stream) (i.e. alluvium McGraw-Hill, 1978); typically occurring beneath or alongside a current channel, or in a buried old or palaeo-channel of the river.

***Anaerobic* -** a process such as a reaction taking place which requires the absence of oxygen; also used in the sense of being able to use an energy source other than oxygen as in anaerobic bacteria (Chambers, 1996).

***Anisotropic* -** having some physical property that varies with direction (McGraw-Hill, 1978).

***Annual plant* -** a plant which completes its life cycle within one year or one growing season; i.e. the seed germinates and grows into a plant which produces flowers, sets seed and dies.

Anuran – tailless, stout-bodied amphibians with long hind limbs for leaping; semiaquatic and terrestrial species, typically called frogs or toads (McGraw-Hill, 1978).

***Aquatic ecosystem* -** defined in the water quality guidelines (DWAF, 1996) as: the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs lakes and wetlands and their fringing vegetation. Terrestrial biota, other than humans dependent on aquatic systems for their survival, are included in this definition.

Aquifer - A geological formation which has structures or textures that hold water or permit appreciable water movement through them (National Water Act, 1998). A saturated stratum which contains intergranular interstices, or a fissure / fracture or a system of interconnected fissures / fractures capable of transmitting groundwater rapidly enough to supply a borehole or spring directly (McGraw-Hill, 1978).

***Aquifer dependent ecosystems* -** ecosystems which depend on groundwater in, or discharging from, an aquifer. They are distinctive because of their connection to the aquifer and would be fundamentally altered in terms of their structure and functions if groundwater was no longer available.

***Aquifuge* -** a body of rock which contains no interconnected openings and therefore neither absorbs nor transmits water (McGraw-Hill, 1978).

***Aquitard / aquiclude* -** a saturated body of poorly permeable rock that is capable of slowly absorbing water from and releasing it to an aquifer. It does not transmit water rapidly enough, by itself, to directly supply a borehole or spring (McGraw-Hill, 1978).

Artesian aquifer - a confined aquifer where the water is under sufficient hydrostatic pressure for the water-level to rise to the surface and overflow from a borehole drilled into it (Chambers, 1996); see also *confined aquifer*. The borehole is termed an artesian borehole and the aquifer may also feed artesian springs.

Azonal vegetation type – a vegetation type whose boundaries are determined by non-climatic factors such as the availability of extra moisture in addition to the rainfall (e.g. groundwater discharge, high water tables, a river floodplain receiving lateral drainage and flows from upstream), or harsh growing conditions such as a salt marsh or very shallow soils over hard rock which cannot store much rainfall (Bailey, 1995 in Smith and Davidson, 2003).

***Bank storage* -** water that percolates laterally from a river in flood into the adjacent geological material, some of which may flow back into the river during low-flow conditions (Ward, 1975). In some situations at least part of the water in bank storage may come from lateral inflow from the surrounding area.

***Baseflow* -** the volume of water in the stream when at its minimum or base level of flow; this is the level to which the stream flow returns between storms; in climates with seasonal rainfall it is often treated as the dry season flow; it is commonly viewed as being derived exclusively from groundwater flow or discharge (Ward, 1975, McGraw-Hill, 1978), but may include drainage from deep soil and weathered material; generally synonymous with the term low flow.

***Basic human need* -** the minimum amount of water required to satisfy a person’s basic water requirements, this is currently set at 25 litres per person per day (Gazette ?, 1997).

***Biodiversity* -** a term which encompasses the diversity of living organisms in a system, their interactions and their roles maintaining ecological processes and functions. Formally, there are three components: (a) composition: what is there and how abundant it is; (b) structure: how the units are organised (structured) in space and time; and (c) function: the roles the different units play in maintaining processes and dynamics. These three components are each represented at four different levels or scales of organisations: (i) genes, (ii) species and/or populations, (iii) communities (habitats) or ecosystems and (iv) landscapes (Noss, 1990). In conservation planning the terms composition and structure are combined and called biodiversity pattern.

Biome **-** A broad ecological unit representing major life zones of large areas, characterized by associations of distinctive life forms and plant and animal species (Lincoln *et al*., 1983). In South Africa these are defined mainly by vegetation structure and climate (Low and Rebelo, 1996).

Bowen Ratio – a technique for estimating evaporation from measurements of the gradients in the mean air temperatures and water vapour pressure deficits over short periods of time. The gradients are used to estimate the energy and water vapour fluxes in the atmosphere and, thus, the evaporation (Savage *et al*., 1997).

Capillary rise **-** the natural occurrence of water in contact with, but rising above, the water table; caused by the tensional forces in the pore spaces of soil, sediment and rock material i.e. capillary migration (McGraw-Hill, 1978). In fine grained material capillary rise amounts to 2-3 m, but reaches only a couple of centimetres in coarser grained material.

Capillary zone or fringe **-** The lower division of the zone of aeration (vadose zone) that overlies the zone of saturation and in which the pressure of water in the interstices is less than in the atmosphere (McGraw-Hill, 1978). It is situated immediately above the saturated zone (the level where the pressure head is zero) and is also saturated; more accurately called the tension-saturated zone because the water is held in the soil pores against gravity by capillary tension.

Catchment **-** synonymous with a river basin or watershed; an area of land forming a natural drainage basin which channels all the water into a single (surface) outflow (Lincoln *et al*., 1983); though in South Africa the term *mountain catchment* is often used to describe the upper, high yielding portions of a river drainage.

Coastal forest **-** Medium to tall forest vegetation dominated by evergreen trees, creepers and lianas and shrubs, often associated with coastal lakes and swamps. Distributed from Alexandria to the Mozambique border and further up the east coast. In the sense used here it includes the Sand forest of the northern KwaZulu-Natal coastal belt which is dominated by deciduous trees (see Low and Rebelo, 1996).

Confined aquifer **-** an aquifer that is confined between two aquitards, aquicludes or aquifuges. A body of groundwater of which the pressure at its upper surface is greater than that of the atmosphere and of which the upper surface is the bottom of an impermeable layer or a layer of distinctly lower permeability than the material in which the water occurs.

Deep seepage **-** the loss of water from a catchment which is not measured at a gauging weir; it occurs where there are routes for water movement through the underlying soil or geological formations or where a subsurface divide does not coincide with a surface divide. These routes may include preferential pathways or macropores. Much of this water will recharge aquifers, some may remain in the deep unsaturated zone.

Dependency – to rely on, be influenced or determined by (Collins English Dictionary, 1998). In this report it identifies an ecosystem whose composition, structure and functioning would be substantially altered if the availability of groundwater was changed, even if the groundwater was essential only for a short period of time.

Discharge area **-** an area in which subsurface water, including water in the unsaturated and saturated zones, is discharged at the land surface; may be associated with a wetland or a stream.

Disconnected stream **-** not a formal term; a situation when a stream is situated above but not in hydrological contact with local groundwater (Winter *et al*., 1999).

Drawdown **-** the difference between the water table level observed during abstraction and the rest water level when no abstraction is taking place water [m] (McGraw-Hill, 1978).

Eddy correlation – the name of a technique for estimating evaporation by simultaneously, and directly, measuring rapid vertical fluctuations in both the wind speed and air temperature. These values are used to calculate the sensible (measurable) heat fluxes and, in turn, the water vapour fluxes and, thus, the evaporation (Savage *et al*., 1997).

Ecoregion: a region within which there is a relative similarity in the kinds of ecosystems and ecosystem components (biotic and abiotic, aquatic and terrestrial); in this context it describes a region within which the riverine ecosystems can be expected to be similar based on the large-scale geology, geomorphology (terrain types) and vegetation (Kleynhans *et al*. 1999). A hierarchical system is under development beginning with level 1 at a national scale and level 2 nested within level 1.

Ecosystem **-** an interconnected, and interacting system comprising living organisms - including animals, plants, fungi, and micro-organisms - and their non-living environment acting as a single unit (Lincoln *et al*., 1983). The term ecosystem is used very loosely in the literature and is not tied to any particular spatial scale.

Ecotone **-** a transition zone; a region of overlapping plant associations, as that between two biomes or two adjacent ecosystems (for example the forest “fringe” between the true forest and an adjacent grassland) (Lincoln *et al*., 1983).

Effective rainfall **-** see net rainfall.

Effluent *stream* **-** a stream which is fed directly by the surrounding groundwater: the piezometric level is above the stream surface and discharge to the surface feeds the stream (McGraw-Hill, 1978). Also called a gaining stream (Winter *et al*., 1999). See Influent stream and Disconnected stream.

Embolism – a general term for a blockage of a tube (e.g. blood vessel McGraw-Hill, 1978). An embolism forms in a plant when the vessels in the xylem (water transporting tissues) of a plant form gas bubbles because of the high tensions induced by water shortage. Embolisms block the vessels and stop water transport though them. When a large proportion of these vessels are blocked by embolisms the plant cannot supply enough water to its leaves to prevent wilting and death.

Endorheic **-** a term used to describe a closed or blind drainage system, one which has no outlet; many of the highveld pans are endorheic pans (Allan *et al*., 1995).

Ephemeral **-** rivers, streams or pans which are ephemeral are fed by inflows of surface water only during and shortly after rains (McGraw-Hill, 1978) generally for less than 20% of the time; the timing of flows depends on the occurrence of adequate rainfall. There is no baseflow so these are influent features which, in permeable areas, recharge groundwater.

Estuary **-** a partially or fully enclosed body of water, which is open to the sea permanently or periodically, and within which the sea water can be diluted, to an extent that is measurable, with fresh water drained from the land (National Water Act No. 36 of 1998).

Evaporation **-** the total loss of moisture in the form of water vapour (Lincoln *et al*., 1983) from all sources - open water, from the plant surface (interception), through plants (transpiration) and from the soil surface. It involves the transition of water from the liquid phase to the vapour phase. During this process energy (termed latent heat) is absorbed so it can also be expressed in terms of energy exchange. It is usually expressed in units of depth to relate it to rainfall. Symbol E or E_t.

Evapotranspiration - in modern usage is replaced by the term *evaporation* **-** the total loss of water in vapour form from open water, from the plant surface (interception), through plants (transpiration) and from the soil surface (Lincoln *et al*., 1983). Symbol usually E_t or E_{tr}.

Flow recession **-** the rate at which the increase in streamflow after rain returns to the baseflow levels after the flow has peaked (Lee, 1980).

Fractured aquifer **-** an aquifer that owes its water-bearing properties to water storage and flows through fractures in the rock caused by folding and faulting; a type of *secondary aquifer*.

Fluvial **-** relating to or found in rivers (Chambers, 1996); caused by the action of flowing water in a river.

Fynbos **-** This is a colloquial term for the species-rich, typically shrub dominated, indigenous vegetation found on the acidic, nutrient-poor soils derived from Cape sandstones, deep dune sands of the coastal lowlands and granite or shale-derived soils in areas with high rainfall. It is found on the Cape mountains and coastal lowlands between the great escarpment and the coast from the Kamiesberg in the north-west to the Zuurberg near Grahamstown in the east. The communities are made up of one or more of the following typical plant types: tall, evergreen shrubs with medium sized leaves (e.g. Protea family), short to medium height, evergreen shrubs with small tough (sclerophyllous) leaves (e.g. Erica family, legumes, Daisy family) and the leafless, tough, reed-like restios. Annuals are generally rare or absent and there are typically numerous summer-deciduous geophytes (see Low and Rebelo, 1996).

Gaining stream – a stream that is gaining water from the adjacent environment through the discharge of interflow or groundwater or both (Winter *et al*., 1999). Somewhat counter-intuitively called an effluent stream in American groundwater terminology (see effluent stream).

Geohydrological region **-** an area characterised by geological formations with similar geohydrological characteristics (e.g. aquifer types, water levels), and exploitation characteristics. Vegter (1995) has defined 65 geohydrological regions in South Africa.

Geohydrological response unit **-** the smallest spatial unit defined for groundwater based demarcated on the basis of homogeneous responses and the geohydrological region.

Geohydrology **-** the study of the properties, circulation and distribution of groundwater (McGraw-Hill, 1978); in practice used interchangeably with hydrogeology; but in theory hydrogeology is the study of geology from the perspective of its role and influence in hydrology while geohydrology is the study of hydrology from the perspective of the influence on geology.

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

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

Geophyte- plants with perennating parts (buds or organs) located on the plant below the soil surface, as on bulbs or rhizomes (Lincoln *et al*., 1983).

Grassveld – vegetation dominated by grasses and sometimes sedges with a very low cover of woody plants, usually confined to less fire-prone situations; other names include: grassland, pasture, rangeland.

Groundwater – in common usage includes all subsurface water (McGraw-Hill, 1978) but in this document the use of this term is restricted to water in the zone of saturation. It flows into boreholes/wells, emerges as springs, seeps out in streambeds or elsewhere in surface catchments and is not bound to rock (particle) surfaces by forces of adhesion and cohesion. Generally used of water contained in *aquifers*.

Groundwater Dependent Ecosystem – an ecosystem which depends on groundwater discharging from or contained within an aquifer, and is significantly altered by changes in the groundwater regime.

Groundwater discharge **-** the release, or emergence of *groundwater* from an *aquifer* into the unsaturated soil or as surface water springs, wetlands or streams (McGraw-Hill, 1978); also called groundwater flow (Ward, 1975). Discharge areas occur in the lower parts of catchments and may comprise springs or seeps, where groundwater contributes to the surface runoff or streamflow. These areas are synonymous with the source areas of rivers.

Groundwater management unit **-** An area of the catchment which requires consistent management actions to maintain the desired level of use and protection of groundwater (Xu *et al*, 2003).

Groundwater recharge **-** (a) the volume of water added to the zone of saturation (McGraw-Hill, 1978) and (b) those processes leading to the addition of water to the zone of saturation. A recharge area refers to the portion of the catchment where the subsurface water is recharged.

Groundwater region (geohydrological region) **-** A broad geohydrological grouping based on dominant aquifer type (secondary/ primary), lithostratigraphy, physiography and climate. Sixty-four geohydrological regions have been delineated in South Africa (Vegter, 2001)

Groundwater response **unit**: An aquifer unit, or multiple aquifer units, with relatively similar hydrogeological characteristics, including permeability, thickness, storage, attenuation potential and hydrochemistry, and therefore similar responses to anthropogenic and climatic variables.

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

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

Herbaceous plant **-** a plant having the characteristics of a herb which lacks a true woody stem and branches and has no secondary (diameter) growth (Lincoln *et al*., 1983); having the texture or colour of a foliage leaf.

Hierarchy **-** a series of ordered groupings of people or things within a system, arranged one above the other (SOED). See: http://www.isss.org/hierarchy.htm and Nested hierarchy.

Hydraulic conductivity **-** a measure of the ability of a material (here soil and rocks) to transmit water under the influence of gravity and hydraulic forces (McGraw-Hill, 1978). (Loosely synonymous with *permeability*). Units: [length/ time] [metres/day]

Hydraulic gradient **-** the slope of the water table or piezometric surface; expressed as the ratio of the change of hydraulic head divided by the distance between the two points of measurement (McGraw-Hill, 1978) (i.e. dimensionless ratio of Length/Length).

Hydraulic head **-** the height of a column of water above a reference [length] [m].

Hydric soils **-** soils whose formation has been controlled primarily by the soil moisture regime, particularly the duration and frequency of saturation or flooding; the anaerobic conditions often lead to reduction of the iron compounds resulting in orange, yellow or grey colours and mottling in the saturated layers (USDA).

Hydrograph **-** a graphical plot showing a hydrological measurement over a period of time such as the depth or volume of flow (discharge) over a weir (McGraw-Hill, 1978).

Hydrological cycle (water cycle or water system) **-** the continuous circulation of water between oceans, the atmosphere and land; the sun provides the energy that evaporates water from the oceans or land into the atmosphere, while the forces of gravity influence the movement of both surface and subsurface water (National Water Act, No 36 of 1998).

Hydrological year **-** a continuous 12-month period selected to present data so that the peak flows are in the centre of a graph; in South Africa, DWAF use the convention of 1 October to 30 September for summer rainfall areas and 1 April to 31 March in the winter rainfall areas. The hydrological year is numbered according to the calendar year in which October falls (hydrological year 2000 runs from 1 October 2001 to 30 September 2001.

Hydrology **-** the study of the occurrence, properties, circulation and distribution of water on the earth and in the atmosphere (Chambers 1996).

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

Infiltration **-** the process through which water filters through the surface of the soil under the influence of gravity and hydraulic forces (Lincoln *et al*., 1983). Having entered into the soil, the further movement of water is properly termed percolation. The infiltrating water replenishes soil moisture deficiencies on its downward path - care should be taken not to confuse and equate infiltration with groundwater recharge.

Influent stream **-** a stream that is ‘perched’ above the surrounding groundwater to which it is connected and is feeding; also called a losing stream (McGraw-Hill, 1978; Winter *et al*., 1999); i.e. a form of direct recharge of groundwater.

Interception **-** the retention of precipitation on the surfaces on which it lands (e.g. leaves, bark, vegetation, litter, etc.) and its subsequent loss by evaporation (Lincoln *et al*., 1983). Symbol I and sometimes E_i. Some authors include throughfall, leaf drip and stemflow under interception (Ward, 1975).

Interflow **-** refers to the (rapid) lateral movement of subsurface water from rainfall through the soil layers above the water table to a stream or other point where it reaches the surface (McGraw-Hill, 1978); generally synonymous with *subsurface stormflow*. In the context of this report, interflow is considered as temporarily saturated lateral flow in the unsaturated (vadose) zone.

Lacustrine **-** wetlands such as dams and lakes situated in topographic depressions, includes permanent and seasonal forms; in South Africa the term lake is only used for water bodies with a total (open water) area greater than 8 ha (Cowan, 1995).

Landform **-** any physical, recognisable form or feature of the earth’s surface having a characteristic shape and produced by natural causes (Bates and Jackson, 1980).

Leaf area index – the most widely used definition is the ratio of the total area of the leaves on the plant divided by the area of the canopy when projected vertically onto the ground (as though the sun was directly above) (Scurlock *et al*., 2001). For example a leaf-area index of 2.0 means there are 2 m² of projected leaf area per m² of ground. The leaf area is measured as the area of the one (upper) side only unless explicitly indicated otherwise. It is strongly correlated with both the productivity (growth rate) and the transpiration and rainfall interception of a plant or plant community. Abbreviated as LAI.

Legume **-** any member of the pea or legume family (Fabaceae) e.g. beans, peanuts, alfalfa, *Acacia*, peanut-butter cassia; generally key nitrogen fixing plants where the nitrogen is fixed by bacteria living in root nodules.

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

Losing stream **-** a stream with a water level which is higher than the water table in the surrounding groundwater which it is feeding (Winter *et al*., 1999); see also influent stream.

Lysimeter **-** an (experimental) instrument for precise measuring of evaporation; involving the regular measurement of the weight of a block of soil and the plants that grow in it, and water inputs and leakage (McGraw-Hill, 1978).

Macropore flow **-** the movement of water through the *unsaturated* and *saturated* zones in relatively large gaps or channels in the soil and regolith which are too large to be affected by capillary forces (McGraw-Hill, 1978). These include desiccation cracks, fissures and root channels. Flow rates are usually significantly more rapid than *matrix flow*.

Matrix flow - the movement of moisture through interconnected pores under the influence hydraulic gradients and gravity (McGraw-Hill, 1978). Flow rates are therefore governed by factors such as permeability, capillary forces and, in the *unsaturated zone*, moisture content.

Moisture stress – in plant physiology, this a measure of the moisture shortage in the plants tissues and thus of the tension in the water conducting tissues (xylem) in the plant. It is usually measured in units of pressure (mega Pascals or MPa) (Ritchie and Hinckley, 1975).

Nested hierarchy **-** a series of ordered groupings of people or things within a system where the lower levels are fitted completely within the higher levels. See also hierarchy and: http://www.isss.org/hierarchy.htm.

Net rainfall **-** or net precipitation, is usually taken as total rainfall less the net interception loss. This is not necessarily interception because some authors include throughfall and stemflow under interception (Ward, 1975).

Overland flow **-** strictly speaking this refers to rainwater flowing over the land surface (Ward, 1975; McGraw-Hill, 1978); the surface is typically either impervious (e.g. rock), or saturated by preceding rainfall, or the intensity of the rainfall exceeds the soil infiltration rate; the water does not enter the subsurface at any point; in practice it is often used loosely to include all *surface runoff* which may also come from water which has infiltrated the soil. Also called

Hortonian (infiltration excess) flow after the hydrologist Horton who first described the phenomenon.

Overstorey – the upper layer of plants in a vegetation type which is noticeably two or more layered. In a savanna or woodland the tree or shrub layer forms the overstorey

Palustrine **-**freshwater wetland environments other than those along rivers and lakes; includes seasonal and permanent forms; the emergent form has vegetation dominated by growth forms such as low shrubs, reeds, mosses and lichens; the forested form has vegetation dominated by shrubs and forest types (Cowan, 1995).

Perched aquifer – an aquifer that is separated from an underlying body of groundwater by an unsaturated zone (see below).

Perched groundwater **-** unconfined groundwater separated from an underlying main body of groundwater by an [impermeable layer and] unsaturated zone (McGraw-Hill, 1978, A.G.I. glossary).

Perched springs **-** springs which are fed by groundwater discharge from a perched aquifer (McGraw-Hill, 1978).

Perched water table **-** the *water table* on an unconfined *aquifer* separated from an underlying main body of *groundwater* by an *unsaturated zone*, generally perched on and impermeable layer. The watertable of a body of perched groundwater (A.G.I. glossary).

Percolation **-** in soil physics, it is defined as the process by which the water moves through the soil and under-lying material under the influence of gravity and hydraulic forces (McGraw-Hill, 1978). In geohydrology, the term is confined to flow in the unsaturated zone.

Perennial **-** a plant which lives for more than two years (Lincoln *et al*., 1983); herbaceous perennials may have stems and/or leaves which are produced and die back annually, with their underground stems and/or roots remaining alive; woody perennials, e.g. trees and shrubs, have aerial stems which may live for many years. When used for a river, it refers to a river that contains surface water except under very extreme conditions (Uys and O’Keeffe, 1997).

Permeability **-** a measure of the ability of a material to allow a substance to pass through it (McGraw-Hill, 1978). In this context it refers to the ability of soil and rocks to conduct water under the influence of gravity and hydraulic forces. (Synonymous with *Hydraulic conductivity*).

Phreatic *surface* **-** the upper limit of the zone of saturation i.e. the *water table* (McGraw-Hill, 1978) where the water pressure is equivalent to atmospheric pressure.

Phreatic *zone = zone of saturation* **-** a subsurface zone in which all the interstices are filled with water under pressure greater than that of the atmosphere. This zone is separated from the zone of aeration (unsaturated zone) in unconfined aquifers, by the water table (McGraw-Hill, 1978, A.G.I. Glossary).

Phreatophyte **-** a plant with a deep root system which obtains water from the groundwater table or the capillary fringe above the water table (McGraw-Hill, 1978). These plants are often riparian or grow where groundwater tables are within reach of their roots. They typically have high transpiration rates. Obligate phreatophytes are completely dependent on access to groundwater; facultative phreatophytes are species with the ability to develop deep root systems, enabling them to tap deep soil or groundwater resources to maintain high transpiration rates.

Piezometric *level* **-** the elevation to which groundwater levels rise in boreholes that penetrate confined or semi-confined aquifers.

Piezometric surface **-** an imaginary surface representing the piezometric pressure or hydraulic head throughout all or part of a confined or semi-confined aquifer; analogous to the water table of an unconfined aquifer.

Pioneer **-** plant species or community that typically is the first to occupy a site after disturbance or clearing, e.g. after fire or cultivation (Lincoln *et al*., 1983).

Plant growth form – a classification of a plant based on its form or habit, or the shape of the parts (morphology) (McGraw-Hill, 1978) or functional aspects such as the life cycle or leaf longevity (e.g. evergreen versus deciduous) of a plant. For example, the term “life form” was used by the ecologist Raunkiaer to define classes based on the ways in which plants survive drought conditions.

Plant structure **-** the form or type, size, shape and arrangements of the plant parts such as leaves, branches or stems (Lincoln *et al*., 1983). This would include such features as the height of the plant, size and denseness of the canopy and leaf area or *leaf area index*.

Potential evaporation **-** the maximum possible *evaporation* (including *transpiration)* under a given set of circumstances with freely available water (McGraw-Hill, 1978). Generally it is expressed as the amount of water that could be *evaporated* with the energy available under a given set of circumstances and assuming that water is freely available to the vegetation. Symbol PET or PEt.

Precipitation **-** technically the word simply refers to the transition of a substance from one phase to another; in the climatic context it is used broadly for all forms of water deposition on the earth's surface (McGraw-Hill, 1978) including dew, mist, rain, snow and hail. Precipitation is measured in units of depth (mm or inches). Precipitation results in the release of energy (termed latent heat). Symbol P or Ppt.

Preferential flow **-** equivalent to *macropore flow*.

Primary aquifer **-** an *aquifer* in which water moves through the *primary openings* of the geological formation.

Primary openings **-** interstices that were formed contemporaneously with the formation of the sedimentary deposit or rock that contains them. Synonymous with primary porosity. The ability of water to flow to flow through these interstices is termed primary *permeability*.

Quickflow **-** that portion of the increase in stream flow which occurs during or after a storm; synonymous with storm runoff or stormflow (Ward, 1975); by convention, this is not *baseflow* (groundwater discharge).

Recharge **-** see groundwater recharge.

Regolith **-** Technically a layer or body of weathered, fragmented or unconsolidated rock material, whether residual or transported, of variable character and overlying bedrock (Bates and Jackson, 1980). The mantle of fragmented and loose material of residual and / or transported origin, comprising rock debris, alluvium, aeolian deposited soil and *in situ* weathered / decomposed rock. It overlies or covers more solid rock, so-called bedrock (A.G.I glossary). Note that the term *regolith* includes soil, but in this report we generally distinguish between an agricultural soil (upper metre or so with a soil profile with clear horizons) and more mixed, less developed material at deeper levels.

Reference conditions: These describe the natural (un-impacted) characteristics of a water resource. Reference conditions include: water flows (quantities) - in terms of the seasonal and inter-annual variations in water levels – and water quality - the concentration of the key water quality constituents, including their seasonal and inter-annual variability; groundwater / surface water interactions (including recharge and / or discharge); rainfall; and aquifer structure and integrity. Drought conditions are also included (Xu *et al*., 2003).

Reserve **-** the quantity and quality of water required to supply basic needs of people dependent on that resource, and to protect aquatic ecosystems in order to secure ecologically sustainable development and use of water resources (National Water Act No 36 of 1998).

Resource quality **-** the quality of all aspects of a water resource including (a) the quality, pattern, timing, water level and assurance of instream flow, (b) the water quality, including the physical, chemical and biological characteristics of water, (c) the characteristic and condition of the instream and riparian habitat; and (d) the characteristics, condition and distribution of aquatic biota (National Water Act, No 36 of 1998).

Resource Quality Objectives **-** provide goals for water resource management which are set by the Minister during the process of classification of significant water resources. They may relate to all aspects of water resource quality as listed above.

Rest water level **-** the level of water in a borehole not affected by pumping.

Riparian – living or growing by rivers or streams (e.g. on the bank, McGraw-Hill, 1978). The National Water Act contains the following definition: *riparian habitat' includes the physical structure and associated vegetation of the areas associated with a watercourse which are commonly characterised by alluvial soils, and which are inundated or flooded to an extent* *and with a frequency sufficient to support vegetation of species with a composition and physical structure distinct from those of adjacent land areas.*

Riverine wetlands – wetlands associated with rivers and streams, including inland deltas, and both permanent and seasonal forms (Cowan, 1995).

***Roots* -** *tap, sinker, lateral, etc.* **-** the descending axis or parts of a plant, normally below ground (McGraw-Hill, 1978); functions include anchorage, absorption and conduction of water and minerals, and sometimes food storage; roots lack the nodes and internodes found in stems and branches.

Runoff – the water in a stream after rain (McGraw-Hill, 1978). In hydrology this refers to all the surface flow of water from a *catchment* in a stream or river (Ward, 1975); sometimes includes the sub-surface runoff. It is usually used to refer to the (volume of) surface water that leaves a catchment in a period of time. As most catchments are assumed to have no subsurface flow at the measuring point it is generally equivalent to the surface runoff. All forms of runoff are measured in units of volume (m^3 or ft^3) but are sometimes expressed in units of depth (see rainfall equivalents). Common symbol is Q.

***Sand plain fynbos* -** a form of *fynbos* which grows on deep sands and dune fields, usually along the coast but sometimes well inland. Often characterised by the tall, tufted restio species used for thatching (see Low and Rebelo, 1996).

***Saprolite* -** *in situ* chemically weathered, thoroughly decomposed igneous or metamorphic rock (McGraw-Hill, 1978).

Saturated zone – or zone of saturation; commonly defined as the portion of the profile below the *water table* or where the soil pores are saturated with water; more accurately defined as the level at which the pressure in the water is greater than atmospheric pressure (McGraw-Hill, 1978); it thus excludes the *capillary fringe*.

Savanna – a grassland with scattered trees or scattered clumps of trees, that experiences a characteristic long, dry season; most authors suggest that the tree canopy cover should be low (≤10%) and use the term woodland for grassland with a higher canopy cover (Cole, 1986, Low and Rebelo, 1996)

***Seasonal river* -** rivers which only flow reliably during specific periods of the year as determined by the seasonal distribution of rainfall; flow generally occurs between 20 % and 80 % of the time; these rivers generally have a limited baseflow component with little or no groundwater discharge (Uys and O'Keeffe, 1997).

***Secondary aquifer* -** an *aquifer* in which water moves through the *secondary openings* of the geological formation.

***Secondary openings* -** interstices that were formed by processes that affected the rocks after they were formed. Synonymous with secondary porosity. The ability of water to flow through these interstices is termed secondary *permeability*.

Semi-confined aquifer **-** an aquifer that is partly confined by layers of lower permeability material through which recharge and discharge may occur, also referred to as a leaky aquifer.

Seep **-** slow escape or oozing of water (Chambers, 1996); used of a usually small, diffuse wetland area where interflow and groundwater emerges, usually at a slow rate, to become surface flow.

Soil **-** the upper surface layer of the earth comprising decomposed and fragmented rock or unconsolidated sediments, living organisms, organic matter, water and gases with properties attributable to the interaction of its parent material, time, climate, fauna and flora (McGraw-Hill, 1978).

Soil bulk density **-** the mass of an undisturbed soil per unit volume of dry soil i.e. including the soil pores (Lee, 1980); has SI units of kg/m^3.

Soil evaporation **-** the loss of water in vapour form from the surface of the mineral soil (Lee, 1980).

Soil moisture (content) **-** see *soil water*.

Soil porosity **-** the fraction of the total soil volume which is pore space (Lee, 1980).

Soil texture **-** a measure of the size distribution of the particles in the soil; sand is the coarsest fraction and clay the finest; gravel, stones, pebbles and rock are not considered as part of the soil in descriptions of the soil texture. The finer the particles the greater the bulk density and the smaller the soil pores. Texture is very important because it determines how easily water can infiltrate and move through the soil and how much is stored. The small pores of fine soils such as clays hold water very strongly, the large pores of coarse sand hold water very weakly (see also soil water).

Soil water – or soil moisture; water held in the pores (gaps between the particles) in the soil and in the soil itself, in both liquid and vapour phases (McGraw-Hill, 1978). Includes saturated and unsaturated states. Measured as a percentage of the soil dry weight (% by weight) but sometimes as the volume of water as a percentage of the soil volume (% by volume) or as the depth of water per metre depth of soil (m/m).

Soil water terminology **-** **Saturation** occurs when all the soil pores are filled with water. **Field capacity** *(FC)* is the water content of the soil when the hydraulic pressures balance the force of gravity and there is no drainage (Lee, 1980). **Gravitational water** is the water drained by gravity from the soil as the water content decreases from saturation to field capacity. **Permanent wilting point** *(PWP)* is the water content of the soil at which the plants cannot extract any more water and therefore their leaves wilt; they will die if the soil moisture content stays at this level for a while. **Available water** is the water held by the soil between FC and PWP. FC and PWP, and thus the gravitational and available water are mainly determined by the soil texture.

Source area **-** the saturated zone along an effluent stream which generates streamflow (stormflow and baseflow).

Spring – a place, usually a distinct point or small area, where groundwater emerges (McGraw-Hill, 1978), generally as a result of topographical, lithological or structural controls on groundwater movements.

***Stemflow* -** the intercepted water that runs down the surface of the branches and stem of a plant (Ward, 1975).

***Storm response ratios*-** the volume of stormflow (or runoff) relative to the volume of rainfall that generated it.

***Stormflow* -** the increased runoff and water flow which is associated directly with a particular (intense) rainfall event or storm (Lee, 1980). It is the same as the *quickflow* or direct runoff.

***Streamflow* -** the water flowing in a stream or river (Ward, 1975); generally represented by the symbol Q. See also *runoff.*

***Subsurface water* -** all water which occurs beneath the surface of the earth, including soil moisture, liquid water in the vadose zone and groundwater.

Subterranean – situated, occurring or operating beneath the surface of the earth (Chambers, 1996).

***Successional stage* -** in plant ecology, the orderly sequence of changes in a plant community during the development of vegetation in any area. Includes all changes which take place from the initial colonization of a previously unoccupied geographical area through to the maturation of that vegetation (Lincoln *et al*., 1992).

***Succulent* -** A plant which accumulates water in juicy tissues (McGraw-Hill, 1978): fleshy water-storing stems, leaves or roots.

Surface runoff – see *runoff*.

***Tension saturated zone* -** another term for the *capillary fringe*.

***Thicket* -** a very variable vegetation type dominated by evergreen shrubs and trees; vines are often common; in the more open forms the gaps between the shrubs are dominated by annuals and succulents as is the pioneer stage in dune areas. Dune thicket is also known as strandveld (see Low and Rebelo, 1996).

***Throughfall* -** the rainfall that passes right through or drips from the plant canopy (Ward, 1975).

***Transpiration* -** the loss of water vapour from the living cells in the plant through pores (stomata) in the leaves in vapour form (Ward, 1975). Symbol often E_t but sometimes Et.

***Unconfined aquifer* -** see aquifer.

***Understorey* -** trees, shrubs and other plants found beneath the level of the main canopy (overstorey) of a vegetation which has two or more distinct layers (e.g. forest).

***Unsaturated zone* -** the layer(s) of the soil and underlying material where the soil pores are only partially filled with water. Not necessarily composed of soil or regolith only but may also include bodies of fractured bedrock. A subsurface zone containing water under pressure less than that of the atmosphere, including water held by capillary tension. The zone is subdivided into the belt of soil water, the intermediate belt and the capillary fringe (A.G.I. glossary).

***Vadose zone* -** another name for the *unsaturated zone.*

Vapour pressure deficit – or vapour pressure difference; a measure of the water absorption capacity of the air based on the difference between the partial pressure of water vapour if the air were saturated and the ambient water vapour pressure (Lee, 1980). It is usually calculated from the relative humidity and temperature of the air and in units of Pascals (Pa) or millibars (mb). There are ways of estimating it from daily temperature data alone.

***Water course* -** a river or spring; a natural channel in which water flows regularly or intermittently; a wetland, lake or dam into which, or from which water flows; and any collection of water which the Minister may, by notice in the Gazette, declare to be a water course (National Water Act No 36 of 1998).

***Water table* -** the upper surface of the zone of *saturation* of an *unconfined aquifer*; i.e. between the zone of saturation and the zone of aeration (McGraw-Hill, 1978); also known as the free water surface or ground water level. On this surface the hydrostatic pressure is equal to atmospheric pressure (the water table therefore excludes the capillary fringe).

***Water-use efficiency* -** the amount of plant tissue (biomass) produced per unit of water transpired; the usual units are grams per gram.

***Wetland* -** plant community or site with a soil that is flooded for sufficiently long periods for waterlogging to become the dominant factor determining its diagnostic characteristics. Land which is transitionary between terrestrial and aquatic systems, where the water table is usually at or near the surface, or the land is periodically covered with shallow water, and which land in normal circumstances supports or would support vegetation typically adapted to life in saturated soil (National Water Act No 36 of 1998).

***Wetting front* -** the boundary between a body of water from rainfall moving (primarily downwards in the unsaturated zone) from soil it has wetted into the drier soil around it.

***Xerophyte* -** a plant that is adapted to habitats where the water supply is limited (McGraw-Hill, 1978), these habitats can occur even in high rainfall regions.

***Xylem* -** the principal water- and mineral-conducting tissue in vascular plants (McGraw-Hill, 1978); a complex tissue composed of nonliving, lignified tracheids, vessels, and fibres, and their associated parenchyma cells. Xylem may also provide mechanical support, especially in plants with secondary xylem (wood).

***Zonal vegetation type* -** a vegetation type whose boundaries are determined by the integrated influence of the regional climate on plant communities, soil moisture and nutrients, and ecological driving forces such as fire regimes, with climate being the dominant factor (Bailey, 1995 in Smith and Davidson, 2003).

***Zone of aeration* -** another name for the *unsaturated zone*.

***Zone of saturation* -** see phreatic zone.

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