Disclaimer

This report emanates from a project financed by the Water Research Commission (WRC) and is approved for publication. Approval does not signify that the contents necessarily reflect the views and policies of the WRC or the members of the project steering committee, nor does mention of trade names or commercial products constitute endorsement or recommendation for use.
Contents

EXECUTIVE SUMMARY

PROGRESS REPORT

ACKNOWLEDGEMENTS

ABBREVIATIONS

1. SECTION 1: BACKGROUND AND THEORY
1.1 Protecting the Ecological Role of Groundwater
1.2 What is meant by groundwater dependence?
1.3 What types of groundwater dependence are there?
  1.3.1 Ecosystems with direct dependency on groundwater
  1.3.2 Species with indirect dependence
  1.3.3 Dependence and the life-cycle
1.4 How sensitive are plants to changes in the water table depth or spring discharge?
1.5 Overview of groundwater-vegetation interactions
1.6 Preliminary protocol to assess groundwater dependency and set RQOs
1.7 Indicators of groundwater use
  1.7.1 Environmental indicators
  1.7.2 Plant growth form
  1.7.3 Remote sensing techniques
1.8 National Scale Assessment of TGDE probability
1.9 Type Settings for TGDEs in South Africa
  1.9.1 Introduction
  1.9.2 Vegetation as an indicator of groundwater dependent ecosystems
  1.9.3 Hydrogeological type settings

2. SECTION 2: TOOLS FOR ASSESSMENT OF GROUNDWATER USE
2.1 The tool box
2.2 Table 7: Tool-box of Techniques
2.3 Case studies

3. SECTION 3: FIELD STUDIES

REFERENCES

GLOSSARY
List of Figures

Figure 1: Schematic diagram illustrating some typical interactions between vegetation and groundwater ______________________________ 6
Figure 2: Preliminary protocol to identify groundwater dependent vegetation and set RQOs _____________ 7
Figure 3: Probability of Terrestrial Groundwater Dependent Ecosystems based on Groundwater Levels (mbgl) and Moisture Growing Season Duration (days) for South Africa _______________ 20
Figure 4: Mean groundwater levels in South Africa (Vegter, 1995) ________________________________ 20
Figure 5: Moisture Growing Season Duration (days) (FAO, 1978 method as presented in Schultze et al., 1996) _____________ 21
Figure 6: Biomes of South Africa (Low and Rebelo, 1996) ________________________________________ 21
Figure 7: Simplified Hydrogeological Terrains of South Africa based on a grouping of primary lithology. __ 22
Figure 8: Fractured sedimentary terrain: __________________________________________________________________________ 26
Figure 9: Fractured sedimentary terrain: __________________________________________________________________________ 27
Figure 10: Fractured sedimentary terrain: __________________________________________________________________________ 28
Figure 11: Fractured sedimentary terrain: __________________________________________________________________________ 29
Figure 12: Fractured sedimentary terrain: __________________________________________________________________________ 30
Figure 13: Carbonate terrain: _______________________________________________________________________________ 32
Figure 14: A granite terrain with accumulation of weathered colluvial and alluvial deposits _____________ 33
Figure 15: Surficial deposit: _______________________________________________________________________________ 33
Figure 16: Surficial deposit: _______________________________________________________________________________ 35
Figure 17: Surficial deposit: _______________________________________________________________________________ 35
Figure A1: Field Site Location ________________________________________________________________________ 55
Figure A2: Rose diagrams for lineaments on study site A. _____________________________________________ 60
Figure A3: Histogram of NDVI values ______________________________________________________________________ 61
Figure B1: Annual rainfall measured at Atlantis, about 10 km northwest of the study site. ________________ 78
Figure B2: Mean monthly rainfall at Atlantistown for the period shown in Figure B1. ___________________ 78
Figure B3: Cumulative deviations from the mean monthly rainfall from January 1995 to May 2001. ______ 79
Figure B4: A high resolution colour image (scale ±1:2000) showing the location of the study sites (400m radius circles) in the Koeberg Nature Reserve. ____________________________________________ 82
Figure B5: A map of the study sites showing the elevation and the differences in local relief. ____________ 82
Figure B6: Water level monitoring boreholes near vegetation study sites. And the monitoring frequency. _____________ 83
Figure B7: Location of the boreholes used to supply fresh water to the Koeberg Nuclear Power Station and its facilities. _____________ 84
Figure B8: Bowen ratio energy balance system installed at a Rooikrans site (left) and a Strandveld site (right) during summer. ________________________________ 86
Figure B9: pH (KCl) at the strandveld and rooikrans sites ________________________________ 88
Figure B10: Electrical conductivity at the strandveld and rooikrans sites ________________________________ 89
Figure B11: Depths to the watertable measured at monitoring boreholes located close to site A, the strandveld site. ________________________________ 91
Figure B12: Depths to the watertable measured at monitoring boreholes located close to site B, the Rooikrans site. ________________________________ 91
Figure B13: Selected stand structure profiles from the April sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15. 92

Figure B14: Selected stand structure profiles from the August sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15. 92

Figure B14: Selected stand structure profiles from the August sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15. 93

Figure B15: Key to the plant species in the structure profiles 94

Figure B16: Average leaf area indexes (m²/m²) at the dune thicket (Strandveld) and Rooikrans sites during autumn and winter 2001. 94

Figure B17: Summary of the monthly total rainfall (rain), monthly average reference evaporation (ETo), monthly total solar radiation (Rs), and the monthly mean air temperature (Ta) measured from 30 November 2001 to 1 September 2001. 96

Figure B18: Water vapour pressure difference at the strandveld and rooikrans sites during three selected days representing summer, autumn and winter conditions. 97

Figure B19: Water vapour pressure difference at the strandveld and rooikrans sites during autumn 97

Figure B20: Latent heat flux densities at the strandveld and rooikrans sites for three selected days representing summer, autumn and winter conditions. 98

Figure B21: Air temperature profile differences at the strandveld and rooikrans sites for three sample days during summer, autumn and winter 99

Figure B22: Available energy at the strandveld and rooikrans sites, and the difference in the available energy between these sites for three sample days during summer, autumn and winter 100

Figure B23: Net radiation at the strandveld and rooikrans sites, and the difference in the net radiation between these sites for three sample days during summer, autumn and winter 102

Figure B24: Soil heat flux density at the strandveld and rooikrans sites, and the difference in the soil heat flux density between these sites for three sample days during summer, autumn and winter 102

Figure B25: Effective degree of saturation at the strandveld and rooikrans sites at 80 mm and 500 mm below the soil surface for three sample days during summer, autumn and winter 103

Figure B26: Profile soil water content at the strandveld and rooikrans sites over a depth of 1000 mm for three sample days during summer, autumn and winter 103

Figure B27: Percentage of the strandveld and rooikrans profiles (100 cm) filled to its capacity on three sample days during summer, autumn and winter 104

Figure B28: Bowen ratio evaporation (bet) and equilibrium evaporation (eqet) at the strandveld and rooikrans sites for three sample days during summer, autumn and winter 105

List of Tables

Table 2: Minimum Map-able Units Based on the 3 x 3 Spatial Resolution Guideline Factor (adapted from Thompson, 1999) 17

Table 3: Recommended maximum cartographic scales for RS data (adapted from Deane et al., 1989). 17

Table 4: Estimated cost comparison of data types (circa June, 1999). 17

Table 5: Groundwater Levels (mbgl) and Moisture Growing Season Duration (MGSD) (days) 18

Table 6: The types and species of plants that may indicate the presence of groundwater dependent ecosystems in different type-settings. 37

Table 7: Tool-box of Techniques 41

Table A1: Landsat TM & ASTER VNIR spectral characteristics 58
Table B1: Major events in the development of the water management scheme at Atlantis 80
Table B2: Months for which energy balance data were collected at the strandveld and rooikrans sites 84
Table B3: Soil physical properties at the strandveld and rooikrans sites 88
Table B4: Water retention characteristics at the strandveld and rooikrans sites 88
Table B5: Leaf area indexes of the dominant shrub species in the Rooikrans and Thicket stands (m²/m²) based on one m² sample plots 90
Table B6: Summary of available energy and air temperature profile difference at the strandveld and rooikrans site during the three seasons studied 105
This report presents an approach to determining the existence of terrestrial groundwater dependent ecosystems. It discusses what is meant by dependency on groundwater, outlines a proposed protocol to assess dependency and describes various tools which may be used to determine groundwater dependency. Two field studies were carried out to test some of the techniques described.

Terrestrial vegetation systems may be afforded the protection of Resource Quality Objectives under the South African National Water Act. To understand what restrictions may be placed on allocable groundwater we need to understand the nature, extent and degree of dependency of vegetation communities on aquifers.

The **degree** of groundwater dependency may range from total to seasonal. Even seasonal dependency may be critical and could result in the demise of the ecosystem if groundwater was no longer available. The **extent** may be localised to widespread depending on the nature of the aquifer and the water table. It should be noted that even a localised aquifer may support a keystone ecosystem which has an ecological importance greater than its geographical extent. The **nature** of the dependency is possibly the most difficult to predict and may only be realised once an ecosystem has been stressed beyond a critical threshold. For most communities the depth to the water table is likely to be the most important hydrogeological parameter. In coastal areas, salinity may be an important control and in other areas, the presence of nutrients.

A preliminary protocol to assess terrestrial ecosystem dependency on groundwater asks the following key questions:

1. Is groundwater available?
2. Are vegetation communities present in these areas which contrast with the surrounding area?
3. Do these communities use groundwater for all or part of the year?
4. Which hydrogeological parameters are critical to the plants which use groundwater?
5. How would the ecosystem be impacted if groundwater was no longer available?
6. Are these ecosystems important with respect to ecosystem or socio-economic functions in the catchment?

A preliminary national scale map is presented showing the probability of TGDE occurrence based on groundwater levels and moisture growing season duration. This map may be interpreted in the context of hydrogeological terrains and biomes to infer the probability of TGDEs occurring. It may be useful for coarse, catchment level planning.
Simplified South African hydrological terrains, surficial, carbonate, granitic, extrusives, Karoo dykes and sills, and fractured sedimentary terrains, are described with expected type settings for TGDEs.

Section 2 provides a summary of the various techniques available to assess groundwater use by plants. Each tool is considered in terms of its application, what it measures, the costs, environmental constraints and suitability, capacity required, the time required to get meaningful results, the resolution of those results, the format of the outputs, whether it should be used conjunctively with other techniques, the level of previous use world wide and the experience of previous use in South Africa. These aspects are considered most relevant to Catchment Management Agencies (CMAs) and consultants who will need to make decisions about which techniques they should apply to their circumstances.

Section 3 describes two case studies started under this project. The first is in the Kammanassie Nature Reserve and describes a remote sensing application to identify potential groundwater dependent vegetation. Further work is being carried out by DWAF and the Western Cape Nature Conservation Board measuring water stress. This will help to groundtruth the initial results presented here.

The second field study is at Atlantis well field. Water balance studies have been carried out to determine relative water use at sites with groundwater at different depths and different vegetation cover.

It is hoped that this body of work will be useful to hydrogeologists, water managers and ecologists attempting to predict the future impacts of new abstraction schemes and set Resource Quality Objectives to protect groundwater’s ecological role in the catchment.
The original and revised objectives of this project were to:

- Review available literature on terrestrial groundwater dependent ecosystems (TGDEs) in South Africa;
- Develop a conceptual protocol to define the groundwater requirements of TGDEs within the context of the Resource Directed Measures;
- Assess the tools available to determine the occurrence and groundwater requirements of TGDEs;
- Test a selection of these tools at field sites.

Recommendations for further work and coordination of the evolving knowledge base on TGDEs in South Africa are:

- The first stage of the national map could be taken further using remote sensing dry season NDVI data correlated to known groundwater bearing structures where appropriate.
- The results of further testing of the recommended tools and alternate approaches to assessing TGDEs should be collated by DWAF and the knowledge made available to CMAs, DEAT and groundwater practitioners.
- The potential importance of groundwater to terrestrial and riparian vegetation in a water scarce country like South Africa needs to be appreciated by students of ecology and hydrogeology. Eco-hydrology as a whole is emerging as an important area of study and the material presented in this report should be useful to students studying and investigating TGDEs.
- Additional assessment is needed for important, at risk TGDEs. Often the time and resources needed to study these systems are significant. DWAF may need to assist CMAs and WUAs to leverage funding to support assessments of potential impact.

The authors would like to acknowledge the willing collaboration of the following institutions in assisting with the field studies: DWAF, Western Cape Nature Conservation Board, Eskom Koeberg, Cape Metropolitan Council, University of the Western Cape.

We also acknowledge the assistance of Dave Scott, Andiswa Silinga, Ivan Williams, Kathy Pretorius, Caren Jarmain, Godfrey Moses and Jan Bosch, CSIR; Tom Hatton, CSIRO; Noel Merrick, Derek Eamus and Michael Knight of University of Technology, Sydney; Iptieshaam Kippie and Momé Mageman of UWC; Alan Woodford, Toens and partners; Mike Swart, DWAF; Gail Cleaver, WCNCB; Ray Froend, Edith Cowen University.
Finally, we would like to thank the WRC for funding this work, and in particular Kevin Pietersen and George Green for their active support. The Steering Committee is listed below and we would like to acknowledge their assistance:

Mr KC Pietersen - WRC
Dr GC Green - WRC
Mr HMaaren - WRC
Mr EBraune - DWAF
Mr JWentzel - DWAF
Mr JM Nel - DWAF
Mr E van Wyk - DWAF
Mr ZM Dziembowski - DWAF
Dr HMackay - CSIR
Mr RMurray - CSIR
Mr RMeyer - CSIR
Prof BE Kelbe - UZL
Prof DA Hughes - Rhodes University
Mr R Parsons - Parsons & Associates
Mrs M vd Merwe - Committee Secretary
Mrs CM Smit - Coordinator: Water Resource Management
### Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CMAs</td>
<td>Catchment Management Agencies</td>
</tr>
<tr>
<td>DWAF</td>
<td>Department of Waters Affairs &amp; Forestry</td>
</tr>
<tr>
<td>KNP</td>
<td>Kruger National Park</td>
</tr>
<tr>
<td>NBI</td>
<td>National Botanical Institute</td>
</tr>
<tr>
<td>NDVI</td>
<td>Normalised Difference Vegetation Index</td>
</tr>
<tr>
<td>MGSD</td>
<td>Moisture Growing Season Duration</td>
</tr>
<tr>
<td>RDM</td>
<td>Resource Directed Measures</td>
</tr>
<tr>
<td>RQO</td>
<td>Resource Quality Objective</td>
</tr>
<tr>
<td>SASS</td>
<td>South African Scoring System</td>
</tr>
<tr>
<td>SASS5</td>
<td>South Africa Scoring System version 5</td>
</tr>
<tr>
<td>TGDEs</td>
<td>Terrestrial Groundwater Dependent Ecosystems</td>
</tr>
<tr>
<td>TMG</td>
<td>Table Mountain Group</td>
</tr>
<tr>
<td>WCNCB</td>
<td>Western Cape Nature Conservation Board</td>
</tr>
<tr>
<td>WMA</td>
<td>Water Management Area</td>
</tr>
<tr>
<td>WUA</td>
<td>Water User Association</td>
</tr>
</tbody>
</table>
SECTION 1 –

BACKGROUND AND THEORY
1.1 Protecting the ecological role of groundwater

The National Water Act of South Africa (1998) (NWA) is based on principles which include water as an indivisible national asset, the interdependence of all elements of the water cycle, the importance of the ecological functions of all water, and the need to treat all water consistently in law (DWAF, 1996). Water resources in South Africa are protected through the Resource Directed Measures and Source Directed Controls. The generic approach to establishing the Resource Directed Measures (RDM) is valid for all elements of the water cycle. However, there are some aspects that are more difficult to apply to groundwater and need careful treatment.

The RDM represents a shift in thinking from water quality to water resource quality. The resource base includes ecological integrity and functioning. In recognition of this, the Reserve sets aside the quality and quantity of water required by aquatic ecosystems. The ecological support functioning of groundwater is therefore considered only in terms of surface water resources. Groundwater’s role in supporting important terrestrial ecosystems, in particular in the extensive semi-arid parts of South Africa, is not accommodated in the Reserve. These ecosystems may be protected through the other RDM measures, in particular the classification of certain areas requiring special management and RQOs setting management objectives.

To understand what restriction should be placed on allocable groundwater we need to understand the nature, extent and degree of dependency of vegetation communities on aquifers.

The degree of dependency may range from total to seasonal. Even seasonal dependency may be critical and could result in the demise of the ecosystem if groundwater was no longer available.

The extent may be localised to widespread depending on the nature of the aquifer and the water table. It should be noted that even a restricted aquifer may support a keystone ecosystem which has a local importance greater than its geographical extent.

The nature of the dependency is possibly the most difficult to predict and may only be realised once an ecosystem has been stressed beyond a critical threshold. For most communities the depth to the water table is likely to be the most important hydrogeological parameter controlling the availability of groundwater to the plant. In coastal areas, salinity may be an important control and in other areas, the presence of nutrients. These aspects of dependency are discussed in more detail below.

A fundamental tenet of ecology is that ecosystems generally will use resources in proportion to their availability - whether the resource be water, light, nitrogen or anything else - and the availability of different resources will be a significant determinant of their structure, composition and dynamics (see Tilman, 1988 for a review).
Thus, where groundwater is accessible, ecosystems will develop some degree of dependence on it and that dependence is likely to increase with increasing aridity of the associated environment (Hatton and Evans, 1998).

Hatton and Evans make the assumption (and principal criterion) that the degree of dependence is proportional to the fraction of the water budget that the ecosystem derives from groundwater. However, it is argued that seasonal budgets also need to be considered in terms of criticality. Their relevance may be lost if proportional use is considered on an annual scale.

Changes in groundwater availability will, therefore, alter the affected ecosystems, but the nature of the responses is essentially unknown. The changes in ecosystem structure or functioning may be directly proportional to the changes, linear or non-linear, or they may take the form of abrupt changes as critical thresholds are exceeded. The responses may also be similar to those described for state and transition models where ecosystems persist in a particular state or condition and then abruptly switch to a new condition (Westoby et al., 1989). Once the switch has occurred a high degree of intervention may be needed to return the system to its previous state.

Groundwater dependence also includes dependence on water quality. Changes in water chemistry during infiltration or storage in the saturated zone or aquifer generally are substantial (Stanford and Ward, 1993; Sandström, 1996). These changes alter the availability of nutrients relative to the surface water and will also affect the ecosystems that depend on the discharges and the way those discharges vary seasonally (Fraser and Williams, 1998). Studies of the convergence of surface and groundwaters in floodplains and hyporhoeic zones have shown that it is an important factor determining landscape morphologies and their biodiversity and productivity (Stanford & Ward, 1993). The upwelling creates patches of high productivity in the hyporhoeic zones and aquatic systems which support greater animal densities and diversity compared with non-up welling situations. The wetlands document in the DWAF RDM series (Duthie, 1999) also recognises the functional role of nutrients from groundwater in wetlands.

Demonstration of groundwater - use does not necessarily equate to groundwater dependence - by dependence we mean that the ecosystem would be significantly altered and even irreversibly degraded if groundwater availability was to change beyond its "normal" range of fluctuation. In general though there is very little information on this and experimental studies are needed of representative systems before we can assess the degree of dependence with any certainty.
In the interim we can try to identify communities or plant species that indicate groundwater dependence, determine if groundwater is being used and measure the total amount of water being evaporated or transpired as well as moisture stress.

A useful classification of the nature of groundwater dependency is the one developed by Hatton and Evans (1998). This identifies four kinds of ecosystem dependence on groundwater one of which is terrestrial vegetation:

- **Terrestrial vegetation**: dependent on diffuse groundwater discharge through plant root systems where the groundwater body is within the rooting depth of the plants, also called “cryptic” discharge; most noticeable as oasis-type vegetation in arid environments.

- **River base flow systems**: where the character and composition of the aquatic (in-stream) or riparian (near stream) ecosystem depends on groundwater discharge as base (dry season) flows. In many cases the flows also are critical for meeting human needs both directly and by sustaining human enterprises.

- **Wetlands and spring systems**: springs are included here because there is essentially a continuum from a spring which has a definite discharge point to wetlands which depend on diffuse discharge over wide areas. The category would apply to wetlands with a known or likely component of groundwater discharge in their hydrological cycle; at least some endorheic pans and many of the coastal wetlands are examples. Ecosystems dependent on spring discharges are also included in line with the report’s inclusion of their “mound spring” vegetation in this category.

- **Aquifer and cave ecosystems**: the report restricts this to “hypogean life” (subterranean living organisms), including those in the groundwater body itself. These are important but we believe that the potential dependency of any associated above-ground ecosystems also needs to be addressed. Areas with karst geology such as dolomitic rock systems or limestones are examples.

The types described with the Hatton and Evans classification focus on direct dependence - where the organism itself is the direct user of the groundwater. But there are examples where the ability of these species to access groundwater maintains other species in that ecosystem. One example 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, Caldwell and Richards, 1989, Dawson, 1993a,b, Caldwell et al., 1998). 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. The reverse of this phenomenon, transport from moist top- to dryer sub-soil, may allow roots to grow into dry soil and permit plant establishment (Caldwell et al., 1998).
Dependence and the life-cycle

Hydraulic lift will not necessarily involve groundwater and the possibility that the plants may be using deep soil water would need to be tested. The loss of the deep rooted species through, for example, lowering of the water table may therefore result in a collapse or major transformation of such ecosystems. No information was found on the occurrence, extent and importance of this type of interaction in South Africa for plants or other associated organisms.

Plants may differ in their degree of dependence at different stages in their life-cycle. Seedling recruitment is needed to ensure the long-term maintenance of all plant communities. There seems to be very little information on this issue for groundwater dependent plants, but it is known that high rainfall is needed to stimulate seed germination and promote seedling recruitment in Prosopis species (Harding & Bate, 1991, Garcia-Carreño et al., 1992, Le Maitre, 1999). This is thought to be due to the seedling needing sufficient moisture in the profile to enable it to reach the capillary fringe above the water table before the soil layers above it dry out. This would enable it to survive and become independent of rainfall. It is likely that the recruitment of seedlings of many of the indigenous savanna, woodland and karoo tree and shrub species would be subject to the same constraints. If the water table is lowered by abstraction, the depth may exceed the ability of seedlings to reach it, resulting in slow loss of at least the affected species as the adult plants which die are not replaced.

An extensive survey of the available literature and anecdotal information failed to find much information on groundwater dependence of indigenous vegetation in South Africa. Let alone documented cases of sensitivity to manipulation of the water table (Scott and Le Maitre, 1998, Le Maitre et al., 1999). One documented case is based on observations in the Kuiseb River in Namibia from 1979/80 to 1982/83. During this period the flows in the river did not reach the 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 non-riparian species, did not show any signs of mortality, presumably because it is better able to track changing water tables. Faidherbia albida trees apparently were able to keep their roots in contact with the falling water table unlike the mature trees. Subsequent work (Jobst, 1996) suggests that the older trees were dying naturally due to their old age and not due to their inability to adapt their root systems. The lowered water table and reduction in flood frequencies due to dams in the upper reaches was preventing seedling recruitment. Whatever the cause, although the rate of lowering of the water table in this case was about 1 m per year, it still had a significant impact.
1.5 Overview of Groundwater-vegetation Interactions

Most groundwater-vegetation interactions occur in areas with unconfined groundwater, typically involving primary regolith aquifers, or in areas of groundwater discharge (Hatton et al., 1998; Le Maitre et al., 1999) (Figure 1). Essentially, plants can utilise groundwater wherever their roots can access it and this may occur at substantial depths. Many tree and shrub species are deep rooted (5-10 m) and some are capable of reaching water tables at depths of 10-20 m and more (Stone & Kalisz, 1991; Jackson et al., 1996); a number of our indigenous trees (e.g. Acacia species) are likely to be among them. The two record root depths are from finding roots in boreholes in the Kalahari at depths of 68 m for Boscia albitrunca and 60 m for Acacia erioloba (Jennings, 1974). The existence of the boreholes may have influenced the depths reached but they are still impressive.

Groundwater use and dependency by plants may also not be obvious as there is no surface indication of discharge such as springs. Examples of this can be found in the ephemeral river systems of the Kalahari and in Namibia (Bate and Walker, 1993; Ward et al., 1983) and the occurrence of distinctive vegetation along, for example, dolerite dykes (see Scott & Le Maitre, 1998 ch 4).

Riparian zones, especially in semi-arid to arid areas, are important areas for biodiversity, offering refuges and habitat for a variety of organisms (Milton, 1990; Naiman et al., 1993; Morrison et al., 1994, Milton et al., 1997). In many of these areas non-perennial riparian zones are supported by alluvial aquifers and the perennial systems receive a substantial proportion of local groundwater fed baseflow. An example is the Sabie-Sand River system in the Kruger National Park (KNP) where studies done under the KNP Rivers Research Programme have highlighted the key role of the riparian ecosystem in the maintaining the biodiversity and functioning of the adjoining terrestrial ecosystems (Davies et al., 1993; Jewitt et al., 1998). Baseflow separation techniques suggest that groundwater may comprise a substantial proportion of the dry season flow (Vegter, 1995) which is essential for maintaining the riparian vegetation (Birkhead et al., 1997). In many situations riparian plants are tapping groundwater rather than surface flows. Groundwater extraction could have severe impacts on the nature of such differentiated systems.
Afforestation (or conversion of short herbaceous vegetation to a dense, vigorous vegetation) will increase evaporative losses and reduce recharge (B vs A). Pumping of groundwater (C) may reduce discharge and so affect riparian or wetland vegetation (D). Bush clearing will reduce evaporative losses and increase recharge (F vs E). Pumping from rivers or alluvial aquifers (G) can affect riparian vegetation by lowering groundwater levels. Large phreatophytes along rivers or groundwater zones (H) can depress the groundwater locally causing, for instance, diurnal dips in discharge hydrographs. Plantations of trees with access to a near-surface water table, or exploitation of such groundwater, can cause a draw-down and this may reduce the size of adjacent wetlands and their plant composition (I and J).

Figure 1: Schematic diagram illustrating some typical interactions between vegetation and groundwater (Scott & Le Maître, 1998; Le Maître et al., 1999).
1.6 Preliminary Protocol to Assess Groundwater Dependency and Set RQOs

Outlined below is a preliminary protocol to assess the degree of dependency of vegetation on groundwater and appropriate actions to protect those terrestrial ecosystems.

Figure 2: Preliminary protocol to identify groundwater dependent vegetation and set RQOs.
This protocol is based on the following assumptions, which have been discussed earlier in the text:

- If a resource is available, the local ecosystem will use it. Here we have used an example water table depth of 30 mbgl to indicate availability. Very few trees have the ability to tap groundwater at > 10 m in depth, and this cut-off could be used in many settings. However, in the Kalahari roots up to 60 m have been recorded, therefore the local conditions should be taken into account.

- If the resource is available and the ecosystem associated with it contrasts with the surrounding environment (particularly in terms of species ecosystem structure (e.g. height) composition and abundance) it is likely to be making use of the resource.

- The nature of dependency should be determined temporally and in terms of hydrogeological parameters (or key indicators) which, if protected, would safeguard the terrestrial ecosystem functioning of the resource.

- The degree of protection should be decided by the stakeholders in the catchment, taking into account the relative importance of the ecosystem. Thresholds for RQOs will represent different levels of risk to the existence and functioning of the terrestrial ecosystem.

- The degree of dependency and consequent impact caused by reductions in groundwater availability can be inferred from alternate water sources available (e.g. soil moisture) or from the degree of contrast between the GDE and surrounding ecosystems which do not have access to groundwater.

This protocol takes into account the degree and nature of dependency but does not explicitly consider its extent. Extent may influence the stakeholders perception of importance and actual importance of the ecosystem, but not necessarily. It is therefore implied in the final step.

The section describes techniques for screening or searching catchments using indicators - things that can be used to identify areas where there may be groundwater-vegetation interactions. Only water chemistry indicators can conclusively show whether groundwater is being used by the plants and help to determine how much groundwater is being used. Other indicators are indirect and would need to be used in conjunction with water chemistry to confirm groundwater use. The indicators have been divided into two types: those based on aspects of (a) the environment, and (b) the plants. The final section discusses remote sensing techniques and issues around their application.

A summary of the techniques currently available to determine groundwater use by vegetation is given in Section 2. This provides an outline of the ‘toolbox’ which can be used to resolve issues of groundwater dependency.
Environmental indicators are based on general environmental features which indicate that ecosystems may be dependent on groundwater. Essentially, they are based on common sense and the field experience of geohydrologists and ecologists.

1.7.1 Environmental indicators

**Occurrence of groundwater**

The existence of shallow, unconfined aquifers

Plant root systems, especially those of woody plants, can often be 5-10m deep or more and will access and extract soil (unsaturated zone) and groundwater (saturated and capillary zone) throughout the profile (Le Maitre et al., 1999). If there are differences in the composition and structure of ecosystems between areas with “shallow” groundwater and those without, this is an indication that there may be groundwater dependence. Composition includes the mixture of plant species and structure refers to their size or appearance.

One of the most tried and tested methods for analysing secondary aquifer potential is to analyse the structural geology of an area, looking primarily for lineaments and fracture zones. A variety of sharpening transformations and mineral ratios can be performed on remotely sensed digital data to yield information that either directly assists with interpreting geological structure or implies certain key indicators.

**Discharge areas**

Ecosystems or species which occur in association with (potential) discharge areas, for example in topographic low points or along dykes or fault lines are used as groundwater indicators. The availability of groundwater may not be visible on the surface or there may be more typical discharge areas such as springs, oases or riverine (riparian, floodplain) vegetation where groundwater is entering the river. In the case of springs and riparian situations the ecosystems may be particularly dependent on the base flow (dry season discharge) or the proportion, seasonality and variability of the flow regime.

**Soil saturation**

Mineral soils and weathered material that are saturated for periods of time may become anaerobic. Repeated wetting and drying results in an alternation of anaerobic and aerobic conditions and the reduction of iron compounds (Kotze et al., 1996). This often results in distinct colour changes (from reds through orange and yellow to grey and even black mottling and flecking) known as gleying. The denser and more spatially continuous the colour changes, the greater the degree of saturation. This information can be used by suitably trained people to diagnose the frequency and duration of the saturated conditions and a provisional classification was developed by Kotze et al., (1986). This could be a useful technique for determining the likely importance of groundwater when a water table is found but there are no data on, for example, water-levels over time, that can be used to characterise the groundwater regime at that site. This technique has also been advocated for use as one of the criteria for characterising and classifying wetlands (Kotze, 1996; Duthie, 1999). A similar approach is being used by the forestry industry to help determine the boundaries of areas that are to be excluded from afforestation in order to minimise water-use by plantation trees (FIEC., 1995, 1999; Pott, 1997; Sappi, 1998).
In some ecosystems there is an interesting phenomenon that has been called hydraulic lift (see Richards and Caldwell, 1987, Caldwell and Richards, 1989, Caldwell et al., 1998, Dawson, 1993a,b). This occurs where deep-rooted plants (trees, shrubs) can reach and use groundwater. At night, when they are not transpiring, the water in the shallow root systems leaks out into the soil and can sustain other plants that cannot reach the groundwater themselves. Changes in groundwater levels could reduce the amount of water the trees export and adversely affect this type of ecosystem. An indicator of this type of ecosystem would be greater herbaceous cover near deep-rooted plants than in open areas.

Indication of available groundwater generally needs to be confirmed with the establishment of monitoring wells in the vicinity of the potentially dependent community. Water levels would need to be measured to determine a local water balance in conjunction with climatic parameters and riverflow where appropriate.

A conceptual model should be established giving the boundary conditions and local recharge and discharge. Typically this would be modelled numerically to gain a better quantitative understanding of the processes involved.

Groundwater chemistry, particularly isotopes, can also provide valuable direct evidence of groundwater use so groundwater samples would be required. Oxygen - deuterium isotope analyses can be used when there is a contrast in the isotopic signature of the groundwater and soil water or river water. Analyses are also conducted on water in the xylem tissue of the plants. If the xylem water and groundwater have the same isotopic signature, groundwater is being used. Where there is insufficient contrast, artificial tracers such as rubidium may be injected into the groundwater and analysed for in the plant to show groundwater uptake.

A plant has to transpire water to cool its leaves and needs additional water to maintain the water that keeps delicate tissues such as leaves hydrated and prevent them from wilting. The water it transpires has to be replaced with water absorbed by the roots. Transpiration rates are typically greater than the rate at which water is absorbed by the roots and conducted through the plant so a tension builds up in the conducting tissues. This tension is what is described as moisture stress or, more accurately, water potential. The clearest indications of moisture stress are gained by comparing measurements made pre-dawn with measurements made around midday. A plant with free access to groundwater should have lower moisture stress, and a smaller difference between pre-dawn and midday values than one without access. If the plant shows full recovery between midday and pre-dawn then that is strong evidence that it is able to take up sufficient water from somewhere to recover its moisture balance, and that the source could be groundwater.
Plants with deep roots that are able to tap into deep soil moisture or groundwater may show little moisture stress compared with shallow rooted species (Midgley and Bösenberg, 1990; Crombie et al., 1988; Crombie, 1992; Dodd & Bell, 1993). An increase in moisture stress as groundwater availability decreases (e.g. lowering of the water table) would indicate groundwater dependence and could be a good indicator of when the stress is approaching the stage of plant die-back or mortality. A general review of plant moisture stress and its effects, with the emphasis on woody plants, is given by Kozlowski (1992).

The tension or water potential can be measured by taking a part of the plant, typically a section of a shoot or branch, clamping it into a pressure chamber and applying air pressure to one end of the shoot. When the air pressure is equivalent to the tension, the water exudes from the end of the shoot. The air pressure at that moment can be read off a pressure gauge attached to the chamber. The greater the pressure, the greater the effort the plant is making to obtain water. The units of pressure are usually given in MegaPascals (MPa) or in the older literature as Bars. The critical moisture stress values vary greatly between different species, and between seasons in some species, so it is not possible to give typical pressure ranges. Often the relative differences between species and between pre-dawn and midday measurements are more important. A detailed description of the technique is given by Ritchie and Hinckley (1975).

Evaporation, including transpiration (water-use) by plants, is inherently difficult to measure (Kelliher et al., 1993). A wide variety of techniques have been developed for measuring and estimating evaporation (transpiration and interception) directly and indirectly. There are methods for individual plants, vegetation communities and ecosystems. The methods range from empirical indexes based on readily available climatic data to sophisticated techniques based on energy and vapour fluxes. All of these techniques need to be complemented with hydrochemical measurements of the proportion of the water being used by the plants that comes from groundwater sources. See Thorburn et al., (1993) for an example of this kind of study.

One of the key issues with in-situ measurements is in scaling-up these point or small area based estimates to the scale of a landscape, catchment or region. The issues and sources of error are described in general by Rastetter et al., (1992) and specifically for transpiration by Jarvis and McNaughton (1986). The basic rule is that the smaller the sample, the greater the errors in scaling up.

There are numerous techniques for estimating potential evaporation based on climatic variables such as rainfall, temperature, or pan evaporation or combinations of these (Stephenson, 1990). A useful discussion of some of these and their application within the locally developed ACRU model is given by Schläe (1995). One of the simplest is the Linacre (1977) model while more complex ones such as the Penman-Monteith model require detailed meteorological data (see Jarvis & McNaughton, 1986).
The primary use of these indexes is to obtain values of potential, or reference, evaporation with which measurements of actual evaporations can be compared. The minimum requirements for the Linacre model are daily maximum and minimum temperature, altitude and latitude. Some of the simplifications can be replaced with measured values if more detailed climate data are available. This approach is best suited to estimates for areas of a few hectares. Evaporation from smaller areas could be much higher, especially in (seasonally) dry climates, because of the inflow of dry air with high evaporative demand from the surrounding areas – a process known as advection.

One of the most widely used techniques, especially in agricultural applications, is "crop factors" which are empirically determined ratios of the actual to the potential evaporation, usually given as a value for each month. Tables of crop factors are available for different crops and vegetation types (e.g. Schulze, 1995, Midgely et al., 1995) but these should be treated with caution because they are only valid under conditions where there is no moisture stress.

There are numerous water balance modelling systems (e.g. Schulze, 1995, Walker and Langridge, 1996, Scholes and Walker, 1993) but a thorough review and assessment of these would require a separate study.

The total evaporation losses - transpiration, interception and soil evaporation - from plant communities can be measured using techniques which directly or indirectly measure the energy balance or vapour fluxes. The two most widely used techniques are called the Bowen Ratio and the Eddy Correlation methods. They are described in detail in CRCCH (1996) and Savage et al. (1997). The Eddy Correlation technique is theoretically more accurate but has proved to be more difficult to use successfully in the field. The Bowen Ratio equipment is more robust and is currently the more widely used in South Africa than Eddy Correlation. It measures vertical gradients in the vapour content and temperature of the air to determine the rate of evaporation.

The community scale techniques minimise the scaling problem inherent in single plant measurements but they require large areas (>4 hectares) with a homogenous vegetation canopy and no abrupt changes in topography to ensure that the measured vapour fluxes are representative of that community.

The method is difficult to use in areas with tall vegetation and not suitable for narrow riparian strips. This will be a significant constraint on their application to most groundwater dependent communities. For more information on the theory, constraints and applications under local conditions see Savage et al., (1997). The time required for proper sampling, and the level of skills required means that the methods are best suited to comprehensive reserve determinations. Short-term sampling can be done but the reliability of the resulting evaporation estimates will be significantly reduced.
1.7.2 **Plant growth form**

**Root system**

There is a strong association between plant growth forms and the nature of their root systems. Plants with succulent leaves and stems and most herbaceous plants generally do not have root systems which are deeper than about 2.5-3.5 metres. Woody shrubs and trees, especially evergreen trees, often have tap or sinker roots that can reach 5-10m depth and not infrequently more than 20 m. These values should only be used as guidelines because they are based on single, often ad hoc observations rather than systematic samples. The presence of shrubs and trees, particularly evergreen species, in areas with a rainfall of less than 500 mm may indicate groundwater use and dependence.

Indigenous tree and shrub genera that often have deep roots include Acacia, Boschia, Olea, and Rhus and exotics include Eucalyptus and Prosopis.

**Rooting depth**

**Wood anatomy & wood structure**

The structure of the woody tissues of plants that are tolerant of water shortages or water stress differ from those that are not (Carquist, 1977, Tyree and Sperry, 1989, Tyree & Ewers, 1991, Jarbeau et al., 1995). This is particularly true of phreatophytic species and of tap and sinker roots which are specialized for conducting large quantities of water (Higgins et al., 1987, Pate et al., 1995). Wood anatomy can therefore be used to indicate whether a species is deep rooted and likely to be using groundwater.

The structure of the water conducting vessels, xylem, in the wood of shallow-rooted species has been shown to be highly resistant to the formation of embolisms (gas bubbles) under moisture stress whereas the xylem of deep-rooted species was found to be relatively susceptible (Davis, 1995; Davis & Mooney, 1986; Pockman et al., 1995). The only published local study using this technique was of drought tolerance in Eucalyptus clones by vander Willigen and Pammenter (1998). This technique can be used to screen species to identify those which are both likely to use groundwater and susceptible to embolisms and thus groundwater dependent. This technique provides a measure of the plants ability to tolerate moisture stress without air bubbles (embolisms) forming in and blocking the woody conducting tissue (Sperry et al., 1998). The susceptibility of a plants woody tissues to embolisms can be measured by comparing hydraulic flow rates through the conducting tissue before and after the plant has been subjected to a known moisture stress.
Plants that depend on groundwater to survive (e.g., phreatophytes) may have low resistance to the formation of embolisms because they do not normally experience much moisture stress. One technique consists of an apparatus for clamping stem or shoot sections, applying a tension to initiate embolisms and then applying water under pressure to determine hydraulic flow rates.

Whether or not a plant is evergreen can provide an indication of dependence on groundwater, especially in areas with less than about 500 mm of rainfall or a distinct seasonal drought or both. Leaf temperatures have to be kept at sub-lethal levels by the cooling effect of water evaporation during transpiration. If there is too little water then the leaves have to be shed. Thus an evergreen tree in an area with mainly leafless trees must have some source of water. The habit of pre-rains flowering and new leaf growth in many savannah tree species appears to be associated with deep root systems which can access moisture in the deep soil layers and regolith (Cole, 1986) or even groundwater.

The volume of water transpired by plants is directly related to the leaf area of the plant (Wullschleger et al., 1998 give a recent review for trees), at least within a species, and sometimes across a surprising range of species within a genus (Hatton and Evans, 1998). Thus a high leaf area can indicate access to large volumes of water especially if similar plants in adjacent areas have much lower leaf areas. The most obvious example is plants in oases or in the dry river beds in the interior. Likewise, plants with a high leaf area index, a large area of leaf per unit area of canopy (essentially a dense canopy), are likely to indicate relatively free access to water. The leaf area index can be estimated using remote sensing.

The most common remotely sensed index is the Normalized Difference Vegetation Index (NDVI). This technique is implemented with many different sensor outputs to produce reliable vegetation estimates, worldwide. Modifications have been made to NDVI to compensate for soil background effects atmospheric noise resulting in a wide diversity of estimation techniques.

Terill Ray, in his Internet published document, A FAQ of Vegetation in Remote Sensing, suggests that NDVI is the most suitable for obtaining a quick estimate of vegetation in an image. He goes on to say that PVI (Perpendicular Vegetation Index), although normally suffering from a poor dynamic range is often more effective than NDVI in areas of low vegetation cover. The SAVI (Soil Adjusted Vegetation Index) and the MSAVI (Modified Soil Adjusted Vegetation Index) both take into consideration the effects of background soil effect and, as was discovered later, the effects of senescent vegetation.
Purevdorj et al., (1998), also conclude that the uses of SAVI, TSAVI (Transformed Soil Adjusted Vegetation Index) and MSAVI all resulted in a significant reduction of the errors of the estimate caused by soil brightness compared with NDVI for very low percentage vegetation cover and cover of bare soil. If the characteristics of the soil line are available, the TSAVI provides a more accurate estimate of vegetation cover. If no information on soil line characteristics is available, NDVI gives the best estimate of the percent vegetation cover for a wide range of grass densities and SAVI can be used for estimating vegetation cover at very low densities (Purevdorj et al., 1998).

These points have great importance with regard to estimating vegetation cover in a South African context as the wide variety of biomes featured here stretch from fynbos environments of the Southern Cape and Semi-tropical forests of the Maputo corridor to the sparsely vegetated Karoo. Unfortunately, the relative merits of the many vegetation indices are beyond the scope of this discussion.

**Single plant water measurement**

Single plant transpiration can be estimated in two ways (a) Single leaves or small shoots where the measured transpiration needs to be scaled up to the whole plant (using the transpiration per unit leaf area) and over several species to an entire plant community. (b) The measurement of the transpiration of an entire plant by measuring the rate of water flow through a section of a stem, or the entire stem, of a plant. Sapflow measurement techniques are described by CRCCH (1996) and Smith and Allen (1996). If a water-balance is needed then these techniques need to be supplemented with additional information on rainfall losses through interception.

**Transpiration measurement**

The first technique uses small chambers that can enclose a single leaf or sometimes a shoot of a plant. The change in humidity of the air blown through the chamber is used to calculate transpiration. For a good overview of the techniques and requirements see Pearcy et al., (1989). A significant problem with this approach is that of scaling the leaf-level measurements to the whole canopy of a single plant and then to a plant community. Species mixtures add to the complexity and the potential for errors in scaling up.

**Sapflow measurement**

The second technique involves two different methods which are both based on the same principle. In each case heaters and temperature sensors are inserted into the conducting tissue of a plant or placed around a stem or shoot (CRCCH, 1996, Smith and Allen, 1996, Greenspan nd). The sap is warmed by the heater and the difference in heat conduction rates down and up the stem indicates the flow-rate of the sap. One approach uses continuous heating over a certain period and the other uses a short pulse of heat. The flow rate is converted to a volume of water based on the sapwood area of the measured stem or shoot and the total sapwood area of the sampled plant. The sapwood area can be estimated from a known relationship or measured on a cross section of the sampled shoot or stem.
The estimated volumes should preferably be calibrated by measuring actual volumes used simultaneously (Olbrich, 1991, Smith and Allen, 1996). The technique can be used for mixed species stands if all the important species are measured. The measurement of a number of whole plants or discrete plant units (e.g. a stem of a reed plant) reduces the potential errors in data scaling significantly. For a recent review of the methodology see Smith and Allen (1996).

Both techniques are normally used in combination with a weather station that records climatic variables (radiation, vapour pressure deficit) so that the relationship between transpiration and climatic variables can be modelled.

Remote sensing is the technology of acquiring data and information about an object or phenomena by a device that is not in physical contact with it or gathering information about the Earth and its environment from a distance. The observations that will be discussed here are either digital or photographic and made from fixed platforms onboard satellites or mounted in aircraft. Some sensors capture image data in visible areas of the electro-magnetic spectrum (EMS) whilst others ‘see’ further into the EMS; near infrared (NIR), infrared (IR) and thermal wavelengths for example. All of the systems outlined here are passive systems, or methods that detect reflected radiation rather than reading actively transmitted signals – active systems e.g. radar. The toolbox outlines capabilities of earth observation (EO) sensors available in South Africa. They cover a range of scales and prices. This table and the following text should be used in conjunction with Tables 3 and 4 that show minimum mappable unit and approximate maximum scale, (Thompson, 1999 and Deane et al., 1989).

Remote sensing can be used for a wide variety of environmental monitoring applications. Table 2 lists the most common satellites for which data are readily available in Southern Africa, and that are the most suitable for the sensing of groundwater dependent vegetation. They vary from spatially very coarse data, such as the SPOT Vegetation sensor, to very fine resolution imagery such as IKONOS.

The pricing of such imagery varies greatly and unfortunately often governs the applicability of satellite data within a project framework. As with most cases, choice of remotely sensed data used is dependant upon suitability to the application and at what scale mapping is to be carried out. Another consideration is the continuity of data. It is often prudent to research the satellite programme as a whole when purchasing a lesser-known data type. Problems may arise if repeat data is required and the satellite has been decommissioned or the series discontinued. This is especially important where a project is focused around monitoring or time series data.
In this context, remote sensing is compared on a cost-benefit scale with equivalent scale mapping in the field. To make a direct comparison, the data costs plus any processing time with some field validation must be weighed against the costs of sending a team into the field to manually map the data and capture it upon return.

The options outlined in the table below cover a variety of scales from low spatial resolution, wide spatial extent to very high resolution, limited spatial extent image products. Hence, the following section will look at the implementation of earth observation satellites along this sliding scale.

**Table 2: Minimum Map-able Units Based on the 3 x 3 Spatial Resolution Guideline Factor**
(adapted from Thompson, 1999)

<table>
<thead>
<tr>
<th>Sensor type</th>
<th>Pixel / ground Resolution (metres)</th>
<th>Equivalent Area</th>
<th>Effective minimum map-able unit (metres)</th>
<th>Equivalent area (approx)</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT Pan</td>
<td>10 x 10</td>
<td>0.01 ha</td>
<td>30 x 30</td>
<td>0.09 ha</td>
</tr>
<tr>
<td>SPOT XS</td>
<td>20 x 20</td>
<td>0.04 ha</td>
<td>60 x 60</td>
<td>0.36 ha</td>
</tr>
<tr>
<td>SPOT Vegetation</td>
<td>1000 x 1000</td>
<td>100ha</td>
<td>3000 x 3000</td>
<td>300ha</td>
</tr>
<tr>
<td>LANDSAT TM</td>
<td>30 x 30</td>
<td>0.09 ha</td>
<td>90 x 90</td>
<td>0.81 ha</td>
</tr>
<tr>
<td>LANDSAT MSS</td>
<td>79 x 79</td>
<td>0.62ha</td>
<td>237 x 237</td>
<td>5.6 ha</td>
</tr>
<tr>
<td>IKONOS 1</td>
<td>4 x 4</td>
<td>0.0016</td>
<td>12 x 12</td>
<td>0.0144ha</td>
</tr>
</tbody>
</table>

**Table 3: Recommended maximum cartographic scales for RS data** (adapted from Deane et al., 1989).

<table>
<thead>
<tr>
<th>Sensor / data</th>
<th>Ground resolution (metres)</th>
<th>Maximum cartographic operating scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT Pan</td>
<td>10</td>
<td>1:30 000</td>
</tr>
<tr>
<td>SPOT XS</td>
<td>20</td>
<td>1:60 000</td>
</tr>
<tr>
<td>LANDSAT TM</td>
<td>30</td>
<td>1:90 000</td>
</tr>
<tr>
<td>LANDSAT MSS</td>
<td>80</td>
<td>1:240 000</td>
</tr>
<tr>
<td>IKONOS 1</td>
<td>4</td>
<td>1:50 000 – 1:2 500</td>
</tr>
</tbody>
</table>

**Table 4: Estimated cost comparison of data types** (circa June, 1999).

<table>
<thead>
<tr>
<th>Sensor / data</th>
<th>Ground resolution</th>
<th>Cost per square kilometre</th>
</tr>
</thead>
<tbody>
<tr>
<td>SPOT (2/3) Pan</td>
<td>10 x 10</td>
<td>R3.26</td>
</tr>
<tr>
<td>SPOT (2/3) XS</td>
<td>20 x 20</td>
<td>R2.79</td>
</tr>
<tr>
<td>SPOT (4) Onboard pan/XS merge</td>
<td>10 x 10</td>
<td>R5.88</td>
</tr>
<tr>
<td>LANDSAT TM</td>
<td>30 x 30</td>
<td>R0.35</td>
</tr>
<tr>
<td>LANDSAT ETM**</td>
<td>30 x 30</td>
<td>R1.12</td>
</tr>
<tr>
<td>LANDSAT MSS</td>
<td>79 x 79</td>
<td>R0.0144</td>
</tr>
<tr>
<td>IKONOS 1†</td>
<td>4 x 4</td>
<td>R511 – R1358</td>
</tr>
<tr>
<td>1:10 000 Aerial photography‡</td>
<td>-</td>
<td>R61</td>
</tr>
</tbody>
</table>

* Current price. Only available from EDC in the US.
+ Current price.
$ Based on project specific flight of an area 20 x 40 km.
To perform vegetation analyses on a national or regional scale, looking at general vegetation trends and in particular vegetation change, Landsat MSS would be ideal. This is primarily because the area covered in each overpass is quite large (185 x 180 km) and the data is relatively, more cost effective ($210 per scene for 4 spectral bands). SPOT Vegetation is another alternative that provides vast swaths of data (2250 x 2250 km) in 4 spectral bands, finely tuned to detect vegetation patterns and changes. Both of these satellites have coarse spatial resolution of 1 km limiting their use to broader scale projects.

To approach mapping at standard catchment scale (1:10 000 – 1:100 000) Landsat TM and SPOT 3/4 HRVIR data are more suitable. These two products are the most commonly used commercially available earth observation satellite data in circulation. SPOT offers finer spatial resolution but is hindered by price and spatial coverage (60 x 60 km). Landsat TM, meanwhile, is nine times larger per scene (185 km x 185 km) and considerably cheaper. It is slightly coarser in spatial resolution (30 m pixels rather than SPOT’s 20 m in multi-spectral mode) but has a greater spectral resolution with 3 additional bands to SPOT’s 4 multi-spectral bands. Landsat 7’s new Enhanced Thematic Mapper Plus (ETM+) also draws closer to the SPOT’s spatial resolution in many ways as it now also incorporates a panchromatic band that images the earth at 15 m (SPOT Pan = 10 m).

A coarse, national scale map has been prepared as part of this project to indicate the probability of occurrence of TGDEs based on two indicators:

- Water levels - the prime limiting factor for groundwater availability and use by plants
- Moisture growing season duration (MGSD) as a cumulative indicator of the availability of alternate water in the form of soil moisture.

The map has been compiled by rating the two indicators as indicated in this table below:

<table>
<thead>
<tr>
<th>Water levels (mbgl)</th>
<th>Moisture growing season (Days)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>25-50</td>
</tr>
<tr>
<td>Rating</td>
<td>10</td>
</tr>
<tr>
<td>0-10</td>
<td>10</td>
</tr>
<tr>
<td>10-20</td>
<td>8</td>
</tr>
<tr>
<td>20-30</td>
<td>6</td>
</tr>
<tr>
<td>30-50</td>
<td>4</td>
</tr>
<tr>
<td>50-70</td>
<td>2</td>
</tr>
<tr>
<td>&gt;70</td>
<td>1</td>
</tr>
</tbody>
</table>

Table 5: Groundwater Levels (mbgl) and Moisture Growing Season Duration (MGSD) (days)
The data sets used to compile the map were:

- Water levels from Vegter's Groundwater regions of South Africa (1995)

The groundwater levels are annual means based on the National Groundwater Data Base (Vegter, 1995). The assumption is therefore made that groundwater is available at these mean levels during the dry season when most TGDEs would be most dependent on groundwater resources. A more realistic estimate could be made using mean dry season groundwater levels.

MGSD is calculated based on the FAO (1978) method using hypothetical daily values of precipitation and evaporation estimated by Fourier Analysis of long-term data from weather stations. The coefficient of variation for MGSD is highest in the more arid Northern Cape (CV % 84) and Free State (CV % 63) and least in KZN (CV % 18) and Mpumalanga (CV %17).

The resolution of this map is 1:9 000 000 therefore the indications are very coarse. However, it is hoped that this will give an initial indication of terrestrial ecological groundwater use for planning purposes.

This assessment assumes that the nature of the dependency is on groundwater availability during the dry season. It is possible that TGDEs may occur in shallow groundwater areas where a physiochemical dependency exists (e.g. salinity, trace elements). This requires further research.

A greater level of confidence in the probability of TGDE occurrence could be gained by correlating this map to a remotely sensed NDVI data set. Furthermore, the probability of groundwater use could be varied by biome (Figure 5) depending on the typical rooting depths, or by hydrogeological terrain, as a better level of understanding is gained on the typical habitats for TGDEs in the different areas of South Africa.

[Colour maps may be viewed on either the CSIR Water Programme or the WRC website.]
Figure 3: Probability of Terrestrial Groundwater Dependent Ecosystems based on Groundwater Levels (mbgl) and Moisture Growing Season Duration (days) for South Africa.

Figure 4: Mean groundwater levels in South Africa (Vegter, 1995).
Figure 5: Moisture Growing Season Duration (days) (FAO, 1978 method as presented in Schultze et al., 1996)

Figure 6: Biomes of South Africa (Low and Rebelo, 1996)
Figure 7: Simplified Hydrogeological Terrains of South Africa based on a grouping of primary lithology.
1.9 **Type Settings for TGDEs in South Africa**

### 1.9.1 Introduction

This section develops an approach to characterising the likely occurrence and importance of groundwater in selected hydrogeological type-settings in South Africa. Much of this work has to be based on inference because hydrogeological studies typically identify relatively large aquifers with recharge rates and storage volumes which permit sustained use, high transmissivities which are required for acceptable pumping rates and quality parameters which make them acceptable for human and agricultural use. The amount and quality of the groundwater required to meet the needs of TGDEs may differ markedly from these requirements, although important sources of groundwater near the surface (<30 m deep), or which have surface discharge areas, are highly likely to be associated with important TGDEs.

At a landscape scale the nature, recharge and discharge patterns of groundwater systems are primarily related to the groundwater storage capacity and flow systems. These, in turn, are determined by the nature of the underlying geology (both lithological and structural properties), the degree of formation of soils and regolith by weathering, and geomorphology (see also Partridge and Maud, 1987). These features will also determine the significance of the role of interflow and groundwater in the surface water systems draining these areas. Shallow soils over impermeable bedrock will have limited storage and typically give rise to seasonal streams. Deeply weathered profiles or extensively fractured bedrock will tend to store large volumes of water and support sustained flows through interflow or groundwater discharge. The type-settings described below show these features and identify where important groundwater-dependent ecosystems (TGDEs) may occur in typical hydrogeological terrains. The broad, landscape scale geomorphological features can be used as the basis for a suite of type-settings that can be used to illustrate the likely locations and types of TGDEs.

### 1.9.2 Vegetation as an Indicator of Groundwater Dependent Ecosystems

There has been no systematic research into plant types or species that may be indicators of groundwater dependent ecosystems although a number of species are used informally by hydrogeologists as indicators when siting boreholes (Scott and Le Maitre, 1998). Wetland vegetation generally has been well documented (see Cowan, 1995; Rodgers, 1997) and there have been some surveys of plant species that are associated with riparian situations (Aocks, 1976, 1988; Milton, 1990; Eekhout et al., 1997; O’Connor, 2001) as well as the chapters on the different biomes in Cowling et al. (1997a).

There are a number of problems associated with using wetland or riparian species to indicate groundwater dependent ecosystems. In most cases the importance of groundwater to the wetlands is not well understood or simply unknown. An exception is the Zululand coastal plain where there have been several studies of groundwater dynamics and interactions with the adjacent lakes (Rodgers, 1997) and the less well studied but similar Knysna-Wilderness lake systems (Scott and Le Maitre, 1998, Kelbe et al., 2001).
As there already are provisional guidelines for reserve determination for wetlands (Duthie, 1999), and these will have to be followed for any ecologically significant wetland, they will not be dealt with in any detail here.

The apparent dependence of many floodplain and riparian species on groundwater, especially during the dry season and low flow conditions is often unappreciated. In many cases, particularly in grassland and savanna vegetation types, the association with river systems may be due to them being more protected from fire (e.g. rocky river beds) rather than dependence on groundwater per se. Many of the species listed under the karoo and savanna vegetation types also may occur in dryland situations in areas with an annual rainfall of more than about 400-500 mm. The same applies in cases where there are deep soils or weathered material (regolith). In these situations the plants may not be dependent on the underlying groundwater because the moisture stored in the vadose (unsaturated) layer is sufficient to meet their needs.

The occurrence of reeds (Phragmites, Typha) typically indicates a true wetland or perennial river but there are areas where they occur in what may appear to be a dryland situation and will be dependent on the groundwater (D Le Maitre pers. obs.). In arid dryland and alluvial environments parasitic plants (e.g Loranthus, Viscum in the canopy, Thesium on roots) are largely confined to riparian zones (Milton, 1990), indicating that they can only occur where the species they parasitise have a reliable water source. A provisional list of species in different geological settings and representative vegetation types is given in Table 6.

Groundwater is involved in the landscape-scale development of soil catenas in savanna areas, particularly the Miombo-type woodlands and “dambo” systems which are particularly prominent on the basement granites (see Scholes, 1997), but the role of groundwater in these systems is not well understood. Forest vegetation may indicate groundwater but, because the occurrence of forest also is associated with a range of other factors (e.g. protection from fire, frost free areas, generally high rainfall conditions) (Midgley et al., 1997), each case needs to be examined individually. However, dune and swamp forest vegetation are indicators of ground (and surface) water availability and could be sensitive to changes in the depth to the water table. Groundwater may play an important role in mangrove, estuarine and marine ecosystems but this is an area that still requires research.

The hydrogeological terrains in South Africa outlined in Figure 7 are based on the simplified geology (primary lithology) divided into broad classes according to aquifer types. The terrains are:

- Surficial (including coastal, Kalahari and alluvial);
- Carbonate (dolomites and limestone);
- Basement complex;
- Extrusives (Karoo basalts);
- Younger granites;
1.9.4 Fractured sedimentary terrains

Suggested type-settings for TGDEs are described within different hydrogeological terrains. Three of the classes of hydrogeological terrains are not dealt with individually in the descriptions namely the basement complex, extrusives and Karoo dykes and sills. The basement complex is a rather heterogenous group, mostly marked by their great age and the high degree of weathering and modification they have undergone. Examples of the basement complex can be seen in the Nama Group underlying the Cape Supergroup and in the granites at the base of the Mpumalanga escarpment. The extrusives and intrusives are dealt with in the context of the associated country and surrounding rock types. For example, the fractured sedimentary terrains of the Karoo which have been altered by the formation of dykes, sills or cappings. These intrusions have weathered and eroded to form the typical Karoo landform that is illustrated. The examples from the escarpment both have cappings formed from extruded lava.

The geology of South Africa is dominated by fractured sedimentary rocks, particularly the Karoo sediments which are dominated by shales. These sedimentary layers are found in areas with a wide range of climates and with a wide range of vegetation types. Examples have been selected from:

- the Cape Supergroup (including Table Mountain Group) with its relatively high volumes of water storage and unique vegetation (Cowling et al., 1997b; Weaver and Talma, 2001)
- the semi-arid to arid Karoo region; and
- two locations along the escarpment, both of which have very steep rainfall gradients and a range of vegetation types.

**Table Mountain Group**

The TMG is illustrated at two different scales: regional systems which follow the major structures as best exemplified in the north-west trending mountain ranges (Figure 8); and a more detailed local scale view. (Figure 9). Quartzites, which typify the TMG, weather very slowly, giving rise to generally shallow, rocky and highly permeable soils. Aquifer storage is associated with the highly fractured brittle quartzites.
Groundwater discharge from discrete fractures results in complex discharge patterns with marshes and seepages occurring at various points along slopes, at changes in slopes and in localised flat areas. The coarse, rocky, colluvial and alluvial deposits formed from the quartzites result in many streams which appear and disappear as surface flows, particularly on the alluvial fans that are a prominent feature in many valleys. The major regional fault zones provide storage for substantial volumes of groundwater to significant depths.

Figure 8: Fractured sedimentary terrain:
A typical Cape Supergroup geohydrological setting in the Cape Fold Belt. The major geological formations are dominated by the shales and quartzites of the Table Mountain Group. The flow paths of groundwater and the location of groundwater dependent ecosystems are indicated. Note the orographically controlled trend in rainfall.

Figure 8 shows the complex folded structure of both the basement formations and the quartzites and shale layers which overlie them. Groundwater may follow regional flow paths, along fault zones and lithological contacts, emerging a considerable distance away from the recharge areas. Groundwater which follows deep paths may be heated and emerge as hot springs, a number of which occur in association with the TMG (Vegter, 1995; Weaver and Talma, 2000). The thickness of the quartzites, up to 1 800 m for the Peninsula formation alone, means that considerable quantities of water can be transmitted. The other types of water-bearing formation are the unconsolidated sands, and the underlying formations, of the coastal lowlands as shown on the left in the type setting. Groundwater-dependent ecosystems are shown at points where the groundwater is discharged, or the water table is sufficiently shallow for plant roots to reach it.
Figure 9: Fractured sedimentary terrain:
A typical Table Mountain Group geohydrological type-setting setting showing the major geological formations and the flow paths, likely discharge areas for groundwater and the associated groundwater dependent ecosystems.

The flow regimes in montane seeps and marshes tend to be variable, depending on the storage and flow patterns in the localised fracture systems that discharge into them (Figure 9). Greater and more sustained discharges occur where there are larger fault systems and on the contacts between the base of the quartzites and the shales or basement rocks. The result is a range of groundwater discharge regimes, from ephemeral to wet-season only to perennial springs and wetlands. The diverse regimes, in turn, support a range of groundwater-dependent ecosystem types with different sensitivities to changes in these regimes. A number of plant and animal species have adapted to the differing environments, many occurring only in particular kinds of situations. Many of the shrub species can develop deep root systems (Le Maitre et al., 1999) and could be using groundwater in the underlying rock fractures. They may also be able to develop deep root systems in the weathered granites and reach groundwater there as well. Many of the streams have developed extensive alluvial fans and the occurrence of potentially deep rooted species on these fans away from streamlines suggests that they may be using groundwater in these deposits. For more information on a study in this type-setting see Field Study A.
The Karoo contains a series of formations with shales as the dominant lithology. Shales weather to relatively impermeable material, which combined with the low recharge, results in low yielding groundwater resources which may still be critical for vegetation (Hodgson, 1986; Van Tonder and Kirchner, 1990; Vegter, 1992). The main sources of groundwater are restricted to the particular situations described below. The profile shown here (Figure 10) is of a typical ‘koppie’ from the eastern and southern regions of the Karoo where there are numerous intrusive dolerite dykes and sills. The top of the koppie is formed by an extrusive dolerite sill overlying sandstone. Both rock types are highly resistant to erosion compared with the shales but weathering can result in the formation of cracks which allow some water to percolate through these layers. The next layer is of fractured shale where limited recharge occurs along preferential fractured pathways, but most will flow through the colluvial material which has accumulated on the slopes of the koppie. Some of this water will flow out on the shale-quartzite contact zone at the base of the shale. Water accumulating in the lower shale formation is trapped by the dolerite dyke, raising the water-table towards the surface. The groundwater may appear on the surface at one or more points along the dyke. Fractures created by tectonic movements created pathways for dolerite intrusion. This fracturing, combined with heating from dolerite intrusion, which further fractured and altered the shale in the contact zone, creating a relatively large storage capacity (Acocks, 1988; Hodgson, 1986). There are surficial alluvial deposits which can store limited quantities of water (Vegter, 1992). Relatively impermeable layers of fine sediments in the alluvial deposits may prevent water percolation and retain perched groundwater bodies in...
the alluvial deposits, although the water table itself may be substantially lower. This storage can vary from temporary perched groundwater storage which is replenished when the ephemeral river flows to more permanent storage. In situations where the river is seasonal there may be sufficient water to maintain water in the alluvial deposits all year round as is also the case with the rare perennial rivers in this environment.

These environments generally have low rainfall so groundwater dependent ecosystems typically occur as patches or linear strips of vegetation types that are taller and/or more lush than those in adjacent areas. This is shown by the presence of vegetation at the break of slope and above the shale-quartzite contact zone and on the upslope side of the dolerite sill. There is also vegetation along the alluvial deposits and woody species which have deep roots that can penetrate rock fractures and cracks to reach the groundwater at substantial depths. The gallery vegetation along the rivers is very limited in extent but is important ecologically and socio-economically (Milton, 1990; Scott and Le Maitre, 1998; Milton et al., 1997).

**Figure 11: Fractured sedimentary terrain:**
A cross-section of the Mpumalanga escarpment near Mount Anderson showing the complex layering of the geological formations, the possible location of groundwater and the associated TGDEs. Note the presence of a dolomitic formation above the quartzites. The dolomites can store and convey large volumes of groundwater.

The geology of this part of the escarpment is more complex than the KwaZulu-Natal Drakensberg (see below) and the formations also dip sharply to the west (Deall et al., 1989). There are also several diabase intrusions but these have not been shown. The upper formation is extrusive basalt (Andesite) which caps the underlying layers and forms
the gently undulating western rim of the Highveld (Figure 11). The Pretoria Group comprises alternating layers of quartzites and shales. The erosion resistant quartzites and conglomerate form cliffs, particularly immediately below the basalts. The shales are highly jointed and have become deeply weathered. Studies in small catchments near Sabie have found that plantation tree roots can reach depths of 10s of metres in these shales and extract the relatively large volumes of water stored there (Dye and Poulter, 1991; Scott and Lesch, 1997). The underlying dolomites contain large volumes of water in solution cavities and contain several extensive cave systems. The Black Reef quartzites are erosion resistant but tend to weather along joints, thus providing flow routes for groundwater and access for roots. North-south streams often follow the softer shales overlaying this quartzite and separating it from the dolomites. The basement granites form the undulating landscape that typifies this part of the lowveld. They are deeply weathered (Lageat and Robb, 1984) and can store large volumes of water in the higher rainfall areas along the escarpment (Dye, 1996). Some of the river systems have accumulated deep and extensive alluvial deposits (e.g. Sand River), others run largely over bedrock (e.g. Sabie, Blyde) but most vary along their length.

The complex geology results in a number of settings where there may be TGDEs, particularly at the contacts between the different formations and in the carbonate (dolomitic) terrains. There may also be TGDEs on the basement granites where there is shallow groundwater. Many of the rivers have well-developed riparian forests which would be dependent on combinations of lateral inflows of groundwater and outflow from rivers into the alluvial deposits in the riverbed, banks and floodplain.

![Figure 12: Fractured sedimentary terrain](image)

A similar section to that in Figure 11 showing the geological formations of the KwaZulu-Natal Drakensberg, the flows of groundwater and the likely location of TGDEs.
The geology of the Drakensberg Mountains in KwaZulu-Natal is dominated by the massive extruded basalt capping which has an average thickness of 1.350 m in this area (Bainbridge et al., 1986) (Figure 12). The lava outflows which formed the basalts were the result of a period of intense volcanic activity during the breakup of Gondwanaland about 200 million years ago. The basalts have become heavily weathered and have formed deeply incised valleys and steep slopes during subsequent erosion cycles (Partridge and Maud, 1987). Regolith up to 22m deep was recorded near a ridge top in the Cathedral Peak catchment VI and the depth decreased rapidly downslope (Everson et al., 1998), suggesting that erosion rates have exceeded weathering rates. The basalts overlie the hard sandstones (Clarens formation) which form numerous caves, especially at the contact with the easily eroded mudstones and shales of the underlying Elliot formation. The alternating layers of hard sandstone and shale in the fractured sedimentary rocks of the Molteno formation result in a series of terraces and flat-topped ridges. The upper part of the next formation comprises soft shales and mudstones over erosion resistant sandstones which form plateaux and cliffs.

The deep soils and regolith of the basalts show very high rates of subsurface water movement, especially unsaturated flow as part of subsurface stormflow (interflow) (Everson et al., 1998). The profiles store substantial volumes of water in both the unsaturated (vadose) zone and saturated zone which are the main source of the sustained flows during the dry season. Groundwater tends to emerge as springs and stream (eyes) at breaks (abrupt changes) in the slope. The weathering resistant sandstone underlying the basalt forms a less permeable layer and the groundwater emerges as seeps and springs on the contact zone. Similar features, probably with much lower groundwater yields, occur on the layered shale (or mudstone) and sandstones in the lower formations.

The types of TGDEs will probably be very similar to those on the Mpumalanga escarpment but the particular situations may differ. Deep weathering and the presence of abundant moisture allows deep-rooted plants to flourish but they generally are limited to kloofs and other sites which provide protection from the frequent fires.

Carbonate terrains are an important groundwater source in South Africa, but are generally limited to Northern Cape, North West, Gauteng and southern Western Cape provinces. The most important are the Karst systems which store large volumes of groundwater. Karst systems are formed when carbonate rock formations are dissolved by water with the resulting formation of cavities, caves, underground drainage and sink-holes (Vegter, 2001). In South Africa the main karst systems are formed in:

- the dolomites which extend from the north-western highveld westwards towards the Limpopo, and parts of the eastern escarpment (see below),
- and in the limestone formations found mainly near the coast, particularly the Agulhas and Zululand coastal plains.
1.9.6 Granites, Gneisses and Bushveld Igneous Complex

Dolomite
Breccia
Soil
Saturated sediment
Groundwater and river
Rainfall, groundwater flow
Water table

Figure 13: Carbonate terrain:

A cross-section of a karst formation illustrating the major geohydrological features and the location of groundwater dependent systems. The dolomites are easily weathered and have cracks which can be penetrated to great depths by the roots of deep-rooted species. The dolomites store large volumes and may sustain a high diversity of organisms, many of which may be endemic.

The karst systems are best developed in the dolomite areas of the West Rand where there are numerous cave systems and sinkholes. The dolomite is highly soluble and jointed and roots can easily penetrate as far as the water table, even if it is deep (Figure 13).

There have been hydrogeological studies in dolomitic areas but they have focused on water abstraction and the structural stability of the rock formations where large volumes of water have been pumped out to permit mining operations. The dominant terrestrial vegetation is Rocky Highveld Grassland which has a prominent wood component and pockets of bushveld (Low and Rebelo, 1996).

Some dolomitic areas of the country are bounded into groundwater ‘compartments’ by intruded dykes. At these barriers to groundwater flow, discharge occurs and spring lines with associated wetlands and drainage channels have been noted to support unique faunal and floral communities (Nel et al., 2002). The associated terrestrial fringe of these aquatic habitats is groundwater dependent and results in cryptic discharge.

Granites and gneisses are found in a number of areas spread across South Africa, including:
- the Western Cape where they are found mostly on the lower mountain slopes and the coastal lowlands in association with dune thicket, sand plain and limestone fynbos, and renosterveld;
- parts of Namaqualand with succulent karoo vegetation.
1.9.7 Surficial deposits

- the Upington area with typical nama karoo; and
- the north-western parts of the country with savanna (bushveld) and grassland vegetation.

![Figure 14: A granite terrain with accumulation of weathered colluvial and alluvial deposits.](image1)

The cross-section that has been illustrated (Figure 14) could apply to any of these environments.

**COASTAL AND INLAND DUNE FIELDS**

![Figure 15: Surficial deposit:](image2)

A geohydrological type-setting in a coastal dune field in the southern or western Cape showing the underlying water table and the distribution of the different vegetation communities. Many of the woody species are deep-rooted and likely to be using groundwater even though there is no surface evidence of the underlying groundwater.
South Africa has very limited areas of primary aquifers and these are generally found along the coast: the dune sands and underlying partially and fully consolidated formations of the coastal lowlands of the west coast from the Cape Flats northwards; the Bredasdorp Group in the southern Cape coast; the dune sands of the Port Elizabeth area and the dune areas of the northern Zululand coastal plain (Lubke et al., 1997; Vegter, 1995, 2001). Most of these areas are also characterised by limestones and other calcareous formations but there are extensive acidic (low calcium) sand deposits on the Western Cape lowlands. The vegetation on these systems comprises dune thicket (strandveld) and sand plain fynbos in the Western and Eastern Cape, dune thicket and coastal forest on the dunes at Alexandria (E Cape) and coastal bushveld eastwards to KwaZulu-Natal coast with patches of dune forest on the Zululand coastal plains (Low and Rebelo, 1996; Lubke et al., 1997). All these vegetation types are dominated by woody plants which can have deep root systems that reach the underlying water tables (Figure 15). When the water table is close to, at or above the surface in the dune swales; for at least part of the year, the woody vegetation usually is replaced by typical wetland vegetation (reeds, sedges) or swamp forest (only in the Zululand area). In many cases the use of groundwater is not evident from the vegetation so these are called ‘cryptic’ groundwater dependent ecosystems (Hatton and Evans, 1998). For more information on an example of this type-setting see Field Study B.

KALAHARI BASIN

The Kalahari Basin was filled with sediments during three periods (Partridge and Maud, 1987). The lower beds were deposited during the African erosion cycle towards the end of the Cretaceous, the bulk of the sediments were deposited during the Miocene erosion cycle and the most recent during the Pliocene erosion cycle. Reconstructions of the history of the vegetation on these deposits show that there were repeated cycles of stabilisation by vegetation during wet cycles (Scott et al., 1997) and aeolian redistribution during dry periods. Currently the dunes are stabilised by vegetation in all but the most arid areas except where the vegetation has been overgrazed, destabilising the surface sands (Partridge, 1997). The long history and repeated cycles of mobilisation and stabilisation, together with weathering, has resulted in complex layering of the sediments and the development of calcrites in some settings (see De Vries et al., 2000).

Two type settings are illustrated here. The first is of layered alluvial deposits which occur in the beds of many of the ephemeral rivers of the Kalahari region (Figure 16) and the second is of two apparently dryland situations where certain plants may be using groundwater: one with deep sediments and one with shallow sediments (Figure 17). The river transect only emphasises the complex layering of the alluvial deposits in the river beds, there will also be variations within the dunes themselves. These layers have differential permeabilities, resulting in the creation of perched groundwater bodies after the passage of the episodic floods which characterise these rivers.
Coarse aeolian sand
Alluvial silt and sand
Alluvial sand and gravel - aquifer
Coarse alluvial sand - aquifer
Alluvial clay and silt
Rainfall, groundwater flow
Perched water table

Figure 16 Surficial deposit:
A cross-section of an ephemeral river system in the deep sands deposits of the Kalahari Basin showing the layering of the alluvial sediments, perched storage off groundwater and deep rooting of the woody plants.

Coarse aeolian sand
Consolidated sand
Basement rock
Saturated zone
Rainfall, groundwater flow
Water table

Figure 17 Surficial deposit:
Two cross-sections in the Kalahari Basin showing the deep sands, one where the depth of the sand, and to the water table, is relatively shallow and one where the groundwater is deeper. In both situations there would be no surface evidence of groundwater unless hydraulic lift was maintaining herbaceous communities under the trees.

These perched groundwater bodies can be large enough to supply water for domestic and agricultural purposes. Similar groundwater reserves sustain ecologically and socio-economically important gallery forests on the Kuiseb River (Ward and Breen, 1983; Bate and Walker, 1993; Scott and Le Maitre, 1998; Milton and Dean, 1999) which are ecologically similar to those on the ephemeral rivers of the Kalahari.
Much of the groundwater in the Kalahari basin is situated at depths of 60 m or more (De Vries et al., 2000) where it is unlikely, but not impossible, for deep-rooted woody species such as Acacia erioloba and Boscia albitrunca to reach it (Le Maitre et al., 1999). There are extensive areas where the mean depth is less than 30 m below the surface, for example along the eastern and southern margins of the basin, and the root systems of woody plants are likely to be tapping this water. The water raised by deep-rooted species may also leak out of the roots, a phenomenon known as hydraulic lift (see page 3 for more information on this topic).

The descriptions given above outline the discharge characteristics typical of the various terrains. Groundwater discharge is associated with different landscape and geomorphological features, dictated by the geology and climate. The terrestrial ecosystems dependent on those vary dependent on the biome and ecological setting. Table 6 below, summarises some of the species which may be directly dependent on groundwater in the different terrains.
Table 6: The types and species of plants that may indicate the presence of groundwater dependent ecosystems in different hydrogeological terrains.

The list should be regarded as provisional as many of the species here are known to be riparian or to occur on river floodplains but may not be groundwater dependent. The data sources are given in the text and reference list.

<table>
<thead>
<tr>
<th>Type setting</th>
<th>Vegetation situation</th>
<th>Plant type or species</th>
</tr>
</thead>
<tbody>
<tr>
<td>Any</td>
<td>Most</td>
<td>Reeds: Phragmites australis, P. communis, Typha latifolia</td>
</tr>
<tr>
<td>Fractured sedimentary terrains and extrusives</td>
<td></td>
<td>Restionaceae: Asphodelium nobile, Calopogon paniculatus, Kannomois vigata, Chondropetalum tectorum, Bega capensis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sedges and grasses: Epithisia gracilis, E. quadrangularis, Juncus krausi, Menmuelleria cincta, Scirpus littoralis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Others: Kniphofia uvaria, Osmorhiza asteroides, Wachendorfia thyrsiflora</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trees and shrubs: Bezdela dregeana, B. intermedia, B. lanuginosa, Brunia alopecurides, Brachylaena nervillosa, Claphyria fluminea, C. graminifolia,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>C. hiuta, Eryngium emulsion, Erica species, Leucadendron salicifolium, Metrosideros angustifolia, Oxyris compressa, Psoralea affinis, P. aphylla, P.</td>
</tr>
<tr>
<td></td>
<td></td>
<td>pinnata, Maytenus acuminata, Raphanea melanophloeos, Salix mucronata</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Renosterveld (granites and shales of lower slopes and lowlands)</td>
<td></td>
<td>Sedges and grasses as above</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trees and shrubs: Acacia karoo (in some areas), Buddleja saligna, Grewia species, Maytenus capitata, Olea europaea subsp. africana, Rhus species, Sideroxylon inermis</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Nama Karoo</td>
<td></td>
<td>Sedges and grasses: Cenchrus ciliatius, Cymbodium incompletus, Diggaria species, Hyparrhenia hirta, Juncus species, Panicum stapfianum, Setaria neglecta, Sporobolus fimbriatus</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Others: Asclepias buchenavus, Arida granilloflora, Convolvulus sagittatus, Devera species, Frankenia pulvulenta, Helichrysum pentitozoides, Lotiononislisti, Protasparagus (Asparagus) afficanus, Vahlia capensis</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trees and shrubs: Acacia erioloba, A. karoo, A. mellierra, Diospyros lycioides, Euclea undulata, Grewia robusta, Lycium cinereum, Maytenus polyantha, Parkinsonia africana, Rhigozum obovatum, Rhus species, Salix mucronata, Tamarix usneoides</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Trees and shrubs: Buddleja species, Cithara species, Diospyros species, Erica cooperi, E. aequocellata, Eucalyptus species, E. africana, Leucosidea sericea, Maytenus species, Myrca seratuma, Polemanna montana, Rhus species</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Type setting</td>
<td>Vegetation type and situation</td>
<td>Plant type or species</td>
</tr>
<tr>
<td>----------------------------------------</td>
<td>------------------------------</td>
<td>---------------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Karst systems</td>
<td>Dolomites (western highveld)</td>
<td>Sedges and grasses wetland species. Trees and shrubs: Acacia caffra, Buddleja saligna, Celtis africana, Buddleja saligna, Combretum species, Grewia species, Kiggelia africana, Maytenus heterophylla, M. undata, Rhus species, Ziziphus mucronata</td>
</tr>
<tr>
<td>Savanna and grassland</td>
<td>See species lists for the others savanna and grassland settings</td>
<td></td>
</tr>
<tr>
<td>Surficial deposits</td>
<td>Dune thicket (Western and Eastern Cape)</td>
<td>Sedges and grasses Juncus species, Scirpus species. Trees and shrubs: Euclea species, Diospyros species, Olea europaea subsp. africana, O. exasperata, Pterocelastrus tricuspidatus, Rhus species, Sideroxylon nime.</td>
</tr>
<tr>
<td>Ard savanna: ephemeral rivers</td>
<td>(Kalahari Basin)</td>
<td>Trees and shrubs: Acacia erioloba, A. haematoyxylon, A. karoo, A. mellifera, Boswellia aristata, Buddleja saligna, Diospyros pallens, Eucla pseudobenus, E. undulata, Faidherbia albida, Grewia flava, Lycium hirsutum, Maytenus undulata, Rhus species, Tamarix usneoides, Tarchonanthus camphoratus, Walafrida geniculata, Ziziphus mucronata</td>
</tr>
</tbody>
</table>
SECTION 2 –
TOOLS FOR ASSESSMENT OF GROUNDWATER USE
2.1 The Tool Box

This section provides a summary tool-box of the various techniques discussed in the previous section. Each tool is considered in Table 7 in terms of its application, what it measures, the costs, environmental constraints and suitability, capacity required, the time required to get meaningful results, the resolution of those results, the format of the outputs, whether it should be used conjunctively with other techniques, the level of previous use worldwide and the experience of previous use in South Africa. These aspects are considered most relevant to CMAs and consultants who will need to make decisions about which techniques they should apply to their circumstances.

The costs indicated are based on 2000 prices and give a relative indication of expenses.
## 2.2 Table 7: Tool-box of Techniques

Table 7: Tool-box of Techniques

<table>
<thead>
<tr>
<th>Technique</th>
<th>SPOT Vegetation</th>
<th>Landsat Multi Spectral Scanner MSS</th>
<th>Landsat 4/5 TM (Thematic Mapper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Environmental studies, Agriculture monitoring, Forest monitoring, Global change studies</td>
<td>Landcover/Vegetation/Geological mapping</td>
<td>Landcover/Vegetation/Geological mapping</td>
</tr>
<tr>
<td>Measurable</td>
<td>Reflected radiation indication landscape and vegetation types, Chlorophyll for NDVI (and other VIS)</td>
<td>Reflected radiation indication landscape and vegetation types, Good for regional and large area estimates of Chlorophyll for NDVI (and other VIS)</td>
<td>Reflected radiation indication landscape and vegetation types, Chlorophyll for NDVI (and other VIS)</td>
</tr>
<tr>
<td>Availability</td>
<td>SAC, SAC Archive, USGS EDC</td>
<td>SAC Archive, USGS EDC</td>
<td>SAC Archive, USGS EDC</td>
</tr>
<tr>
<td>Costs - capital operational</td>
<td>€120 (up to 1 million square km), €135 (from 1 – 4 million square km)</td>
<td>$210 per 185x180km scene</td>
<td>$4200 per 185x180km scene</td>
</tr>
<tr>
<td>Environmental constraints/suitability</td>
<td>2,250 x 2,250 km scene size produces images of vast areas (4840000km²), Affected by cloud cover</td>
<td>Covers large area 185 x 185km (34225km²), Affected by cloud cover</td>
<td>Covers large area 185 x 185km (34225km²), Affected by cloud cover</td>
</tr>
<tr>
<td>Capacity required - skills, hardware and software</td>
<td>RS Skills, Capable PC, Image Processing Software</td>
<td>RS Skills, Capable PC, Image Processing Software</td>
<td>RS Skills, Capable PC, Image Processing Software</td>
</tr>
<tr>
<td>Time required to get meaningful results</td>
<td>24 days</td>
<td>1-2 days</td>
<td>1-2 days</td>
</tr>
<tr>
<td>Resolution</td>
<td>1km x 1km MSS</td>
<td>80m Visible – IR</td>
<td>30m Visible-IR 60m Therm IR</td>
</tr>
<tr>
<td>Spectral</td>
<td>Blue: 0.43 to 0.47 µm, Red: 0.61 to 0.68 µm, Near-IR: 0.78 to 0.89 µm, Swave IR: 1.58-1.75 µm</td>
<td>Green: 500 – 600 nm, Red: 600 – 700 nm, R – NIR: 700 – 800 nm, NIR: 800-1100 nm</td>
<td>6 V-IR 1 TIR</td>
</tr>
<tr>
<td>Temporal</td>
<td>14 days, pointable sensor</td>
<td>16 days</td>
<td>16 days repeat pattern</td>
</tr>
<tr>
<td>Output - format and scale (and compatibility with other RDM components).</td>
<td>Digital, statistical and graphical Provincial/national</td>
<td>Digital, statistical and graphical Local – Catchment</td>
<td>Digital, statistical and graphical Local – Catchment</td>
</tr>
<tr>
<td>Conjunctive use</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
</tr>
<tr>
<td>Previous use in SA</td>
<td>Highly limited, if at all</td>
<td>Wide</td>
<td>Wide</td>
</tr>
<tr>
<td>Previous use worldwide</td>
<td>Limited</td>
<td>Wide</td>
<td>Wide</td>
</tr>
<tr>
<td>Summary recommendations</td>
<td>Specially designed to sense vegetation, but spatially too coarse for detecting smaller ecosystems. Very good for large synoptic views and cheap.</td>
<td>Good spectral resolution. Low spatial resolution. Good value mapping product.</td>
<td>Good spectral and temporal resolution. Good cost effective alternative for local scale mapping.</td>
</tr>
</tbody>
</table>

**SAC** – Satellite Applications Centre, CSIR Pretoria  
**USGS EDC** – United States Geological Survey Eros Data Centre  
**NDVI** – Normalised Difference Vegetations Index  
**VI** – Vegetation Index
### Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Landsat 7 ETM+ (Enhanced Thematic Mapper)</th>
<th>SPOT HRVIR</th>
<th>Ikonos</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Landcover</td>
<td>Surveys requiring high-resolution, multi-spectral information</td>
<td>Landcover</td>
</tr>
<tr>
<td></td>
<td>Vegetation</td>
<td>Monitoring of land parcel and cropping patterns, Forest texture, Urban planning</td>
<td>Precision farming</td>
</tr>
<tr>
<td></td>
<td>Geological mapping</td>
<td></td>
<td>High resolution mapping, Telecommunications</td>
</tr>
<tr>
<td></td>
<td>3D Visualisation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Measurable</td>
<td>Reflected radiation indication landscape and vegetation types Chlorophyll for NDVI ( &amp; other VIs)</td>
<td>Reflected radiation indication landscape and vegetation types Chlorophyll NDVI ( &amp; other VIs)</td>
<td>Reflected radiation indication landscape and vegetation types Chlorophyll NDVI ( &amp; other VIs) Greenness Brightness Wetness - Tasseled Cap Texture - Species/community level mapping</td>
</tr>
<tr>
<td>Availability</td>
<td>EDC</td>
<td>SAC</td>
<td>Space Imaging Africa Johannesburg</td>
</tr>
<tr>
<td>Costs - competition/operational</td>
<td>$600 per 185x180km scene</td>
<td>R18000 (60km x 60km)</td>
<td>$70-200 per km² depending upon required accuracy</td>
</tr>
<tr>
<td>Environmental constraints/suitability</td>
<td>Covers large area 185 x 185km (34225km²). Affected by cloud cover</td>
<td>Covers large area 60 x 60km (3600km²). Affected by cloud cover</td>
<td>Variable image size and shape (min. 5x5km). Affected by cloud cover</td>
</tr>
<tr>
<td>Capacity required - skills, hardware and software</td>
<td>RS Skills Capable PC Image Processing Software</td>
<td>RS Skills Capable PC Image Processing Software</td>
<td>Up to the minute RS Skills Capable PC (large amount of storage space Image Processing Software</td>
</tr>
<tr>
<td>Time required to get meaningful results</td>
<td>1-2 days</td>
<td>1-2 days</td>
<td>1-2 days</td>
</tr>
<tr>
<td>Resolution</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spatial</td>
<td>30m MS 15m Pan.</td>
<td>20m MS 10m Pan.</td>
<td>4m MS 1m Pan</td>
</tr>
<tr>
<td>Spectral</td>
<td>6 V-IR 1 TR 1 Pan.</td>
<td>Blue: 0.50 to 0.59 µm Red: 0.61 to 0.68 µm</td>
<td>Blue: 0.45 to 0.53 µm Green: 0.52 to 0.61 µm</td>
</tr>
<tr>
<td></td>
<td>450 – 520 nm</td>
<td>Near-IR: 0.79 to 0.89 µm Swave IR: 1.58-1.75 µm 26 days</td>
<td>Red: 0.64 to 0.71 µm Near-IR: 0.77-0.88 µm Pan: 0.45 – 0.90 µm 1-3 days, pointable sensor</td>
</tr>
<tr>
<td></td>
<td>520 – 600 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>630 – 690 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>760 – 900 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1550 – 1750 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>10400 – 12500 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2080 – 2350 nm</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>500 – 900 nm (Pan)</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>16 days</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Temporal</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Output - format and scale</td>
<td>Digital, statistical and graphical Local - Catchment</td>
<td>Digital, statistical and graphical Local - Catchment</td>
<td>Digital, statistical and graphical Catchment - Sub-local features</td>
</tr>
<tr>
<td>(and compatibility with other components)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Conjunctive use</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
<td>Should be ground-truthed for plant types, lithology &amp; geological feature</td>
</tr>
<tr>
<td>Previous use in SA</td>
<td>Limited</td>
<td>Wide</td>
<td>Highly limited, if at all</td>
</tr>
<tr>
<td>Previous use worldwide</td>
<td>Growing</td>
<td>Wide</td>
<td>Limited (New Product)</td>
</tr>
<tr>
<td>Summary recommendations</td>
<td>Good spectral, and temporal resolution. Most cost effective alternative. Newest Landsat technology. As with TM, but includes new 15m panchromatic band – higher spatial resolution.</td>
<td>Good spatial, spectral and temporal resolution but relatively expensive.</td>
<td>Very fine spatial resolution, extremely expensive. Can be used for a wide variety of large scale mapping projects.</td>
</tr>
</tbody>
</table>
Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Conventional Aerial Photography</th>
<th>Airborne Digital and Hyperspectral Scanners</th>
<th>Airborne Video</th>
</tr>
</thead>
</table>
| **Application** | Urban Planning  
Geological interpretation  
Detailed mapping  
Some vegetation mapping | Landcover  
Precision farming  
Urban/infrastructure planning  
High resolution mapping  
Species mapping | Landcover  
Precision farming  
Urban/infrastructure planning  
High resolution mapping  
Species mapping |
| **Measurable** | Texture  
Species (shape and texture only) | Reflected radiation indication  
landscape and vegetation types  
Chlorophyll  
NDVI (& other Vis)  
Temperature (canopy and surface)  
Lithology/structure | Chlorophyll for NDVI (and Vis)  
and vegetation communities |
| **Availability** | Various aerial photography companies | Hyvista Corporation  
Anglo American Technical Services  
Johannesburg | Agricultural Research Council  
-Pretoria |
| **Costs – capital operatioonal** | Variable – dependent upon survey area and weather | Variable – dependent upon survey area and weather | Variable – dependent upon survey area and weather |
| **Environmental constraints/suitability** | Flexible, but greatly affected by weather | Flexible, but greatly affected by weather | Flexible, but greatly affected by weather |
| **Capacity required – skills, hardware and software** | RS Skills  
Air-photo interpretation skills  
Optional: Stereoscope  
Capable PC  
Image Processing Software | Specific RS Skills  
Capable PC (large amount of storage space  
Specialist Image Processing Software | RS Skills  
Capable PC (large amount of storage space  
Image Processing Software |
| **Time required to get meaningful results** | 2-4 weeks | 1-2 weeks | 2-3 weeks |
| **Resolution** | Generally depends upon altitude.  
Standard, Infrared and thermal film used.  
As required | 3-10m  
126 spectral bands from 0.45 – 2.5µm  
As required | Variable  
Band Centres:  
Blue: 450nm  
Green: 550nm  
Red: 650nm  
Near IR: 750nm  
As required |
| **Output – format and scale (and compatibility with RDM)** | Digital, statistical and graphical  
Local - Single plants | Digital, statistical and graphical  
Catchment - Sub-local feature | Digital, statistical and graphical  
Local - Catchment |
| **Conjunctive use** | Should be ground-truthed for plant types, lithology & geological feature | Should be ground-truthed for plant types, lithology & geological feature | Should be ground-truthed for plant types, lithology & geological feature |
| **Previous use in SA** | Wide | Limited | Wide |
| **Previous use worldwide** | Wide | Wide | Wide |
| **Summary recommendations** | Good high-resolution alternative to digital aerial. A lot of processing required preparing of GIS ready product. Limited spectral properties. | Also very expensive. Excellent spectral resolution. Species identification | Good aerial digital product. Locally available with comparable spectral resolution to SPOT. Geometric rectification and mosaicking –very time consuming |
Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Potential evaporation – Linacre model</th>
<th>Plant community evaporation: Bowen ratio/ Eddy Correlation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Estimating the potential evaporation for an area.</td>
<td>The two techniques are both used to estimate evaporation but differ in the details.</td>
</tr>
<tr>
<td>Measurable</td>
<td>Potential evaporation in millimetres for varying periods of time.</td>
<td>Total evaporation from an area of a homogenous plant community.</td>
</tr>
<tr>
<td>Availability</td>
<td>The equations are available in the published literature (Linacre, 1977; Schulze (1995) presents various versions and discusses their application locally.</td>
<td>The equipment is available from scientific instrument suppliers who have local agents in South Africa.</td>
</tr>
<tr>
<td>Costs - capital operational</td>
<td>Minimal costs of acquiring the data and doing the analysis. Calculations can be done on a normal computer in a spreadsheet.</td>
<td>A Bowen Ratio measurement station currently costs about R70K and needs a standard weather station costing about R15K. Operating costs - fieldwork and servicing instruments once every two weeks.</td>
</tr>
<tr>
<td>Environmental constraints/suitability</td>
<td>Suitable for getting a rough estimate of the maximum amount of water that could be transpired by vegetation with free access to water.</td>
<td>These techniques minimise the scaling problem inherent in single plant measurements but they require large areas (&gt;4 hectares) with a homogenous vegetation canopy and no abrupt changes.</td>
</tr>
<tr>
<td>Capacity required - skills, hardware and software</td>
<td>Ability to use a spreadsheet or write data analysis programmes.</td>
<td>Set up and maintenance - a trained technician. Site selection, data analysis and interpretation - a person with experience in the theory behind the techniques and their constraints. Data processing - statistical packages and spreadsheets.</td>
</tr>
<tr>
<td>Time required to get meaningful results</td>
<td>Depending on the time required to get the relevant daily climate data.</td>
<td>The sampling should preferably be done over a period of 2-3 weeks in each season for a year.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Suitable for estimating for areas of at least a few hectares.</td>
<td>Total evaporation in millimetres for an area of a few hectares (&gt;4 ha).</td>
</tr>
<tr>
<td>Output - format and scale (and compatibility with RDM)</td>
<td>A rough estimate of the volume of water that could be transpired – suitable for a desktop or rapid estimate only.</td>
<td>Evaporation for a plant community. Best suited to comprehensive determinations but if a less accurate estimate was acceptable (e.g. only one season) it could be used for intermediate reserve determinations.</td>
</tr>
<tr>
<td>Conjunctive use</td>
<td>Would need to be combined with an estimate of the proportion of groundwater that is being used.</td>
<td>Suitable climate data for a period of at least one year are needed to be able to model the transpiration over an entire year. Also needs to be combined with water chemistry to determine the proportion groundwater used.</td>
</tr>
<tr>
<td>Previous use in SA</td>
<td>It is a well known formula and is recommended by Schulze (1995) in preference to others like it.</td>
<td>See Savage et al., (1997), Everson et al., (1998).</td>
</tr>
<tr>
<td>Summary recommendations</td>
<td>Only suitable for desktop or rapid assessment.</td>
<td>These are generally accepted as the most accurate methods for measuring actual evaporation from relatively large areas (&gt;4 ha) of a homogenous vegetation community. Provides an integrated measurement of evaporation (i.e. all components are included).</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td><strong>Plant community evaporation: infra-red measurement of canopy temperature</strong></td>
<td><strong>Plant community evaporation: Laser scintillometry</strong></td>
</tr>
<tr>
<td>---------------</td>
<td>-----------------------------------------------------------------------------</td>
<td>--------------------------------------------------</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>The temperature of the leaves can be accurately measured by an infra-red sensor and the difference between the leaf and air temperature can be used to calculate the amount of water being transpired.</td>
<td>This technique measures fluctuations in the intensity of laser beams caused by fluctuations of temperature and humidity. It measures averages over the length of the beam, which can vary from a few metres to several hundred metres. This means that it potentially can be used for both small and large areas, riparian strips and for variable vegetation communities.</td>
</tr>
<tr>
<td><strong>Measurable Output</strong></td>
<td>Canopy transpiration losses.</td>
<td>Evaporation (transpiration and interception).</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>The equipment is available from scientific instrument manufacturers overseas, agent in SA.</td>
<td>Available from scientific instrument suppliers overseas.</td>
</tr>
<tr>
<td><strong>Costs</strong></td>
<td>Capital costs are very high at R480 000 for a single instrument. Will require a weather station costing R15 000 for modeling transpiration and scaling up to annual estimates. Operational costs are likely to be low.</td>
<td>Capital costs are very high at R480 000 for a single instrument. Will require a weather station costing R15 000 for modeling transpiration and scaling up to annual estimates. Operational costs are unknown.</td>
</tr>
<tr>
<td><strong>Environmental Constraints/ Suitability</strong></td>
<td>The sensor has quite a narrow field of view so sampling of several plants or larger areas would require either some way of moving or rotating the sensor or the use of several sensors at one time.</td>
<td>This must still be properly evaluated</td>
</tr>
<tr>
<td><strong>Capacity Required – Skills, Hardware and Software</strong></td>
<td>The equipment can be set up and maintained by a suitable trained technician. Data processing, analysis and interpretation should be done by someone with some training and experience in plant ecophysiology.</td>
<td>Probably will require skilled technicians.</td>
</tr>
<tr>
<td><strong>Time Required to Get Meaningful Results</strong></td>
<td>The sampling should preferably be done over a period of 2-3 weeks in each season for a year; shorter sampling periods are possible but will reduce the accuracy of the estimated transpiration.</td>
<td>This technique will also require sampling across seasons to improve the accuracy of the estimated annual evaporation.</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>From the single plant, or part of a plant canopy, up to much larger areas depending on the sampling strategy and the number of instruments that will be needed.</td>
<td>Potentially from metres to kilometres.</td>
</tr>
<tr>
<td><strong>Output Format and Scale (and Compatibility with RDM)</strong></td>
<td>The need for sampling to include seasonal variations means that this method is best suited to the comprehensive reserve determination. Sampling requirements can be changed if the reduced accuracy of the estimate is acceptable for the level of reserve determination that is needed.</td>
<td>Estimated evaporation. Sampling requirements make it best suited to the comprehensive reserve determination. Short-term sampling should be possible if the loss of accuracy in the estimate is acceptable.</td>
</tr>
<tr>
<td><strong>Conjunctive Use</strong></td>
<td>Suitable climate data for a period of at least one year are needed to be able to model the transpiration over an entire year. Also needs to be combined with water chemistry to determine the proportion of the water that comes from groundwater.</td>
<td>Will need to be combined with weather data so that measurements can be scaled up to a full year. The proportion of the evaporated water that comes from groundwater will have to be measured as well.</td>
</tr>
<tr>
<td><strong>Previous Use in SA</strong></td>
<td>The equipment was recently imported into this country by the CSIR and still has to be tested thoroughly.</td>
<td>This technique is still being tested overseas and has not yet been tested in this country. A proposal to import and test the instrument has been submitted to the Water Research Commission.</td>
</tr>
<tr>
<td><strong>Summary Recommendations</strong></td>
<td>This seems to be a very versatile and promising technique but still has to be tested and assessed under local conditions. Best suited to comprehensive reserve determinations.</td>
<td>This is a very promising technique but still a couple of years from practical use in South Africa.</td>
</tr>
</tbody>
</table>
Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Lysimeter studies on shallow groundwater</th>
<th>Multi-electrode resistivity</th>
<th>Isotope measurements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Application</td>
<td>Intensive research determination of hydrological processes within a particular (and by implication) important plant community.</td>
<td>Resistivity is dependent on soil moisture, soil type, etc. Resistivity changes in resistivity with time can be indirectly related to soil moisture/sol moisture changes and groundwater.</td>
<td>This technique provides a direct measurement of groundwater use by the plant. It can indicate the proportion of groundwater used and seasonal variations.</td>
</tr>
<tr>
<td>Measurable</td>
<td>Direct measurement of water fluxes in saturated and unsaturated zones, and derivation of evaporation by mass balance.</td>
<td>Resistivity of the subsurface changes in resistivity of the subsurface over time</td>
<td>$\delta^{18}O$ ‰ or $\delta^{2}H$ ‰ (SMOW) of water in xylem tissue.</td>
</tr>
<tr>
<td>Availability</td>
<td>Highly specialized equipment, but is readily available.</td>
<td>Equipment, software and operator is available from CSR, Stellenbosch</td>
<td>Analysis can be carried out in Pretoria (CSR, UCTand Wits University). Courier samples.</td>
</tr>
<tr>
<td>Costs - capital operational</td>
<td>High costs associated with intensive and long term studies: costs of installation engineering &amp; equipment (load cells, soil water sensors, data loggers) are roughly R300 000 and would be associated with large human resource costs.</td>
<td>Use of equipment: R1500/day Operator: R2500/day Other running, e.g. S&amp;T: variable</td>
<td>Cost of boreholes to sample groundwater if not established. Analysis: $\delta^{18}O$ and $\delta^{2}H$ in water R150 &amp; R200, plus R50 if extracted from sapwood. Min 3 samples/ plant.</td>
</tr>
<tr>
<td>Environmental constraints/suitability</td>
<td>Intensive, very site specific technique. Would probably be quite suitable only for studies in an important wetland or phreatophyte system characterised by a shallow water table (e.g. reed bed communities in the Kruger Park).</td>
<td>Resistivity contrast between unsaturated and saturated zone. Will not work with high resistive surficial layer.</td>
<td>Significant contrast in $\delta^{18}O$ ‰ or $\delta^{2}H$ ‰ between groundwater and other sources of water.</td>
</tr>
<tr>
<td>Capacity required - skills, hardware and software</td>
<td>Specialised research skills in agricultural or botanical water research; associated with modern high-tech instrumentation skills.</td>
<td>Trained geophysicist to acquire field data, process and interpret data. Multi-electrode resistivity equipment and resistivity inversion software.</td>
<td>Field technicians capable of careful sampling, Isotope analysis and interpretation.</td>
</tr>
<tr>
<td>Time required to get meaningful results</td>
<td>A full annual hydrological cycle ought to be measured, and typically several years. Very high set-up costs involved, so it makes sense to maximise data collection once established.</td>
<td>Immediate data acquisition, processing and analysis: 3 days per 2 linear km. Time lapse measurements every two weeks for first 6 months</td>
<td>Once off sampling – 1 week. Seasonal sampling – 1 year.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Community level information is derived from a micro-plot (1 m$^2$). Variations with time.</td>
<td>Shallow subsurface (root zone). Variations with time.</td>
<td>Plant level, variations with time.</td>
</tr>
<tr>
<td>Output - format and scale (and compatibility with other RDM components)</td>
<td>Full water balance is produced for community represented by the plants in the lysimeter.</td>
<td>Resistivity change due to groundwater use of plants. Soil moisture measurements should be used to calibrate measurements. Also relate to plant transpiration.</td>
<td>Indication of total or proportional groundwater dependency.</td>
</tr>
<tr>
<td>Conjunctive use</td>
<td>Other detailed monitoring, such as of weather, would complement a lysimeter study, to make full use of the investment at the site.</td>
<td>Calibrate with soil moisture, plant type, soil type, transpiration, etc. measurements.</td>
<td>Upscale using measurements of transpiration or RS.</td>
</tr>
<tr>
<td>Previous use in SA</td>
<td>Primarily at Agricultural research stations, and not in relation to groundwater (e.g. Snyman, 199X, Everson et al., 1996)</td>
<td>Mineral exploration (Miningtek, CSR)</td>
<td>Used in forestry and riparian studies.</td>
</tr>
<tr>
<td>Summary recommendations</td>
<td>Research technique suitable for high profile, special cases requiring detailed understanding.</td>
<td>Groundtruth/calibration very important for unique solutions. Rapid data acquisition and interpretation. Time lapse data can be used to indicate changes with time.</td>
<td>Important confirmation of groundwater use where an isotopic contrast exists. Can give quantitative results varying with time. First indication within 1 week.</td>
</tr>
</tbody>
</table>
### Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Rubidium and other artificially applied chemical tracers.</th>
<th>Chemical “finger-printing” to identify sources of water in plants and surface flow.</th>
<th>Modelling of dynamic interaction between groundwater and vegetation communities.</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong></td>
<td>The technique provides a direct qualitative measurement of groundwater use by the plant</td>
<td>Identification of sources of water used by plants, and the relative contributions of the various sources.</td>
<td>Detailed process modelling of vegetation-groundwater interactions using an appropriate process model.</td>
</tr>
<tr>
<td><strong>Measurable</strong></td>
<td>Rubidium concentration in tissue of transpiring leaves</td>
<td>Chemical characteristics of different water sources of water.</td>
<td>Model predictions of several key variables against which model performance can be verified.</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Analysis carried out at ARC labs in major centres. RbCl available from scientific suppliers.</td>
<td>Moderately accessible technique.</td>
<td>Numerous models are available. Choosing the appropriate model is critical, and is determined by nature of system and important variables of interest.</td>
</tr>
<tr>
<td><strong>Costs - capital operational</strong></td>
<td>Cost of injection boreholes if not established. RbCl R400, plus standard = R150. Analysis R20/sample. Min 3 samples/plant.</td>
<td>Water chemistry and stable isotope laboratories already exist.</td>
<td>The major cost is in terms of human resources in learning to understand the model, populate it and calibrate it against measured data.</td>
</tr>
<tr>
<td><strong>Environmental constraints/suitability</strong></td>
<td>Plant roots must intercept injected tracer flow. Amount of tracer to inject may be difficult to determine.</td>
<td>Need to understand and be able to sample the various water sources in a particular situation.</td>
<td>Few. The system needs to be understood adequately for an appropriate model to be chosen, and sufficient input data would need to be available.</td>
</tr>
<tr>
<td><strong>Capacity required - skills, hardware and software</strong></td>
<td>Plant tissue analysis.</td>
<td>Hydrological, water chemistry and isotope chemistry skills.</td>
<td>Specialised geohydrology and soil water hydrology knowledge, and computer skills.</td>
</tr>
<tr>
<td><strong>Time required to get meaningful results</strong></td>
<td>Need at least 2 months for Rb levels to build up.</td>
<td>Relatively quick. One to a few months study.</td>
<td>Variable: from 1 to many months. Probably in the order of 6 months in set-up and developing familiarity with models that are adequately detailed.</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>Plant level.</td>
<td>Essentially a landscape (hydrological unit) scale technique.</td>
<td>Depends on the model, and need not be constrained.</td>
</tr>
<tr>
<td><strong>Output - format and scale (and compatibility with other RDM components)</strong></td>
<td>Indication of groundwater use, but not in proportion to total use.</td>
<td>Numeric; quantification of contribution of water sources. Essentially a landscape scale.</td>
<td>Typically numeric, digital and possibly statistical outputs.</td>
</tr>
<tr>
<td><strong>Conjunctive use</strong></td>
<td>Upscale using measurements of transpiration or RS. Indicate proportional use of groundwater with transpiration measurements and water balance.</td>
<td>To be used with botanical and hydrological techniques to build complete, quantified water balance picture.</td>
<td>Only reliable when model is associated with calibration with observed data, and preferably when done on a study site.</td>
</tr>
<tr>
<td><strong>Previous use in SA</strong></td>
<td>Used in limited forestry studies.</td>
<td>Uncertain; probably quite common in groundwater studies.</td>
<td>Reasonable amount of work, but no focussed work on vegetation and groundwater interactions; no consensus on models.</td>
</tr>
<tr>
<td><strong>Previous use worldwide</strong></td>
<td>Very little documented evidence of use.</td>
<td>Limited use. Paper by Mengis et al., (1999) used as type for this description.</td>
<td>Widespread, with reasonable success where appropriate models are used in association with a detailed study of the real system.</td>
</tr>
<tr>
<td><strong>Summary recommendations</strong></td>
<td>Gives qualitative confirmation of groundwater use. Cannot indicate variation with time. Needs at least 2 months.</td>
<td>Useful where complex water sources are available to vegetation communities.</td>
<td>Modelling is a necessary development to accompany studies, but not replace them, and allows extension of learning to broader scale and other regions.</td>
</tr>
</tbody>
</table>
Table 7 continued

<table>
<thead>
<tr>
<th>Technique</th>
<th>Monitoring of plant response to water table declines</th>
<th>Chloride balance modeling</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Application</strong></td>
<td>Development of management guidelines from direct studies of plant responses to groundwater utilization</td>
<td>Measuring vertical fluxes of water (capillary rise and drainage) in the unsaturated soil (root zone).</td>
</tr>
<tr>
<td><strong>Measurable</strong></td>
<td>Numerous plant growth and health parameters in association with groundwater monitoring, e.g. growth rate, branch die-back, tree mortality, seedling recruitment.</td>
<td>Chloride concentrations in soil extract, soil and irrigation &amp; ground-water, and water balance components (rainfall, drainage and irrigation).</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>Relatively simple and readily available equipment: water monitoring with piezometers (automatic or otherwise) and some plant physiology equipment.</td>
<td>Readily available. Requires standard soil science laboratory equipment.</td>
</tr>
<tr>
<td><strong>Costs - capital</strong></td>
<td>Costs relatively modest, depending on the precise experimental design, using readily available equipment and monitoring methods.</td>
<td>Low capital costs.</td>
</tr>
<tr>
<td><strong>operational</strong></td>
<td>Relatively intensive sampling and monitoring regime.</td>
<td></td>
</tr>
<tr>
<td><strong>Environmental constraints/ suitability</strong></td>
<td>Requires an unaffected control site. It must be possible to effect the rate and extent of groundwater availability. Appropriate to an experimental situation or adaptive management.</td>
<td>Probably dependent on reasonable salinity gradients. Suitable for saline soil zones with a shallow water table where groundwater can rise into the rooting zone.</td>
</tr>
<tr>
<td><strong>Capacity required - skills, hardware and software</strong></td>
<td>Capability to monitor the plant response to stress (biological skills). Groundwater monitoring.</td>
<td>Soil chemistry and laboratory skills.</td>
</tr>
<tr>
<td><strong>Time required to get meaningful results</strong></td>
<td>Longer term research, usually a minimum of one hydrological year.</td>
<td>One to two year study to obtain a balanced picture.</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>Need at least two sites which can be treated independently (abstractions will affect one and not the control site).</td>
<td>Essentially a plot scale method. Usually several sampling points would permit scaling up to the landscape scale with similar groundwater situation exists.</td>
</tr>
<tr>
<td><strong>Output - format and scale</strong></td>
<td>Digital, statistical (e.g. survival statistics) and descriptive. The outputs are plant growth and health criteria. Local catchments – landscape scale.</td>
<td>Numeric.</td>
</tr>
<tr>
<td><strong>Conjunctive use</strong></td>
<td>Suitable for use together with all other approaches.</td>
<td>Needs to be used together with other techniques to build a complete understanding of the water balance and dynamics of vegetation communities on shallow groundwater.</td>
</tr>
<tr>
<td><strong>Previous use in SA</strong></td>
<td>Interesting example on the Limpopo River, with the water supply for Venetia Mine (DeBeers, nd)</td>
<td>None known</td>
</tr>
<tr>
<td><strong>Previous use worldwide</strong></td>
<td>Widely used, particularly in the southwestern USA. Saline soils in Australia and irrigation on the plains of the Indus River, Pakistan.</td>
<td></td>
</tr>
<tr>
<td><strong>Summary recommendations</strong></td>
<td>Sound approach appropriate for situations where shallow groundwater is being or is going to be utilized.</td>
<td>A useful technique for quantifying vertical water fluxes as part of quantifying the water balance and dynamics of vegetation communities on shallow groundwater.</td>
</tr>
<tr>
<td>Technique</td>
<td>Moisture stress</td>
<td>Xylem analysis</td>
</tr>
<tr>
<td>----------------------------</td>
<td>--------------------------------------------------------------------------------</td>
<td>--------------------------------------------------------------------------------</td>
</tr>
<tr>
<td>Application</td>
<td>Measures the degree of moisture stress a plant is experiencing.</td>
<td>Screening woody plant species for susceptibility to changes in groundwater availability.</td>
</tr>
<tr>
<td>Measurable</td>
<td>The hydraulic tension in the plants water conducting tissues at a point in time.</td>
<td>Susceptibility to the formation of embolisms in conducting tissues.</td>
</tr>
<tr>
<td>Availability</td>
<td>Specialist suppliers or could be manufactured by from plans. Organizations such as the ARC, NBI and several universities have the necessary equipment.</td>
<td>Cannot be purchased off-the-shelf at present. Botany departments at universities may do this.</td>
</tr>
<tr>
<td>Costs - capital operational</td>
<td>Costs of purchase probably less than R10 000. Other costs primarily for field work and running costs such as supplies of full gas cylinders.</td>
<td>Not known but the capital costs should be quite low. Other costs primarily for field work and running costs.</td>
</tr>
<tr>
<td>Environmental constraints/ suitability</td>
<td>Best used for screening in areas where the plant species are expected to require groundwater.</td>
<td>Most suitable for investigating woody plant species in semi-arid to arid areas where seasonal moisture stress is likely.</td>
</tr>
<tr>
<td>Capacity required - skills, hardware and software</td>
<td>Robust and simple to use provided the right precautions are taken. Experience is needed to become proficient and to get consistent and repeatable observations.</td>
<td>A technician or plant wood anatomy graduate student. A spreadsheet could be used to summarise the data (Pammenter and van der Willigen, 1998).</td>
</tr>
<tr>
<td>Time required to get meaningful results</td>
<td>Sampling both in the wet season and at the height of the dry season to determine seasonal variation - at least 6 months.</td>
<td>This depends mainly on the time required to get the samples and test them and the availability of the equipment.</td>
</tr>
<tr>
<td>Resolution</td>
<td>Plant species and their habitats.</td>
<td>Plant species and the communities or habitats in which they occur.</td>
</tr>
<tr>
<td>Output - format and scale</td>
<td>A description /map showing the distribution of the indicator species and their associated habitats.</td>
<td>A description /map showing the distribution of the indicator species and their associated habitats.</td>
</tr>
<tr>
<td>Conjunctive use</td>
<td>Source of water, water balance and transpiration measurements.</td>
<td>Need to distinguish the source of the water in the plant, or the tissue composition, and measure transpiration rates.</td>
</tr>
<tr>
<td>Previous use in SA</td>
<td>Used in plant ecophysiological research for more than 20 years - (Smith, 1990), Richardson and Kruger (1990).</td>
<td>Botany Department at the University of Natal (see Pammenter and van der Willigen, 1998).</td>
</tr>
<tr>
<td>Summary recommendations</td>
<td>Can assess whether plants have free access to water and affects of changes.</td>
<td>A promising technique worth pursing as a research project.</td>
</tr>
<tr>
<td><strong>Technique</strong></td>
<td><strong>Whole plant transpiration</strong></td>
<td><strong>Leaf and shoot transpiration</strong></td>
</tr>
<tr>
<td>--------------</td>
<td>-----------------------------</td>
<td>-------------------------------</td>
</tr>
<tr>
<td><strong>Application</strong></td>
<td>Measurements of whole plant water-use based on sap-flow coupled with measurements of climatic variables.</td>
<td>Water loss through transpiration from a single leaf or a small cluster of leaves.</td>
</tr>
<tr>
<td><strong>Measurable</strong></td>
<td>The transpiration of an individual plant, usually woody, expressed as a volume or converted to a depth (mm).</td>
<td>Transpiration by single leaves or small shoot with a few leaves.</td>
</tr>
<tr>
<td><strong>Availability</strong></td>
<td>The equipment is available from suppliers of scientific equipment and there are agents in South Africa.</td>
<td>Commerically available from specialist instrument suppliers. Versions of the instruments are described by Schulze et al., (1982) and Field et al., (1982).</td>
</tr>
<tr>
<td><strong>Costs - capital operational</strong></td>
<td>The full set of sap-flow measuring equipment - approx. R12K. The associated weather station would cost about R15K. Operating costs - fieldwork and servicing instruments once every two weeks.</td>
<td>Capital - R30K. Instruments are delicate and require lots of maintenance. The associated weather station would cost about R15K. Operating costs - travel and field accommodation.</td>
</tr>
<tr>
<td><strong>Environmental constraints/suitability</strong></td>
<td>Best suited to plants with woody stems and more than about 5 mm in diameter. Specialised equipment is available for other plant growth forms but not to stem-less plants like grasses.</td>
<td>Best suited to estimating transpiration for stands of a single species, or mixed species stands if all the important species are measured.</td>
</tr>
<tr>
<td><strong>Capacity required - skills, hardware and software</strong></td>
<td>Technicians can be trained to install and set up the equipment. The interpretation and modelling of the data requires experience and skill and the person requires a sound understanding of plant ecophysiology.</td>
<td>The instruments require trained operators. Interpretation and modelling of the data requires substantial experience and a sound understanding of plant ecophysiology.</td>
</tr>
<tr>
<td><strong>Time required to get meaningful results</strong></td>
<td>The measurements are repeated on several plants over a period of 1-2 weeks and for at least three seasons to allow the transpiration to be estimated for an entire year.</td>
<td>The measurements are repeated on several shoots of several plants over a period of 3-5 days and for at least three seasons to estimate transpiration for an entire year.</td>
</tr>
<tr>
<td><strong>Resolution</strong></td>
<td>The output is the volume of water transpired by a sample of plants and can be expressed per unit area.</td>
<td>Strictly the leaf or shoot but there are procedures for scaling up to the whole canopy and to a community.</td>
</tr>
<tr>
<td><strong>Output - format and scale (and compatibility with other RDM components)</strong></td>
<td>Only suitable for use the comprehensive reserve determination. The sampling periods can be shortened (e.g. to one season) but the reliability of the transpiration estimates will be significantly decreased.</td>
<td>Only suitable for use in the comprehensive reserve determination. Sampling periods can be shortened (e.g. to one season) but the reliability will be significantly decreased.</td>
</tr>
<tr>
<td><strong>Conjunctive use</strong></td>
<td>Data on the sampled plants and plant community to scale up transpiration to a unit area. Suitable climate data for a period of at least one year. Water chemistry to determine the proportion groundwater used.</td>
<td>Data on the sampled plant species and plant community to scale up transpiration to a unit area. Suitable climate data for a period of at least one year. Water chemistry to determine the proportion of groundwater used.</td>
</tr>
<tr>
<td><strong>Summary recommendations</strong></td>
<td>Reliable and relatively simple technique for measuring transpiration for single plants or plant species. Can be scaled up to a plant community where the plant community is dominated by measurable species. Suited to use in comprehensive reserve determinations.</td>
<td>Can be used to estimate plant water use but sap flow techniques are preferred as they reduce the scaling problem. Best suited to the comprehensive reserve determination.</td>
</tr>
</tbody>
</table>
2.3 Case Studies

**CASE 1**: An example of an integrated study of the hydrology and salinity dynamics of a flood plain as affected by timber plantations. Illustrates the use of numerous measurement techniques in a single, well-designed study. Typical of many studies, mostly in Australia, where the full water balance of shallow groundwater sites is determined to assess the role of plants in groundwater discharge.

**Location**: Indus River floodplain, Sindh Province of Pakistan.

**Situation**: Shallow, saline water tables at 1 to 2 m below surface. Recharge from rainfall is unlikely in this semi-arid environment (MAP ~200 mm), but is likely to be from irrigation of the productive farmlands, that are now threatened by saline conditions.

**Study objective**: Can plantations of Acacia spp. and Prosopis spp. be used to increase groundwater discharge (by evaporation) and thereby assist in reclaiming salt-affected land, and at the same time provide a sustainable forestry crop.

**Methods employed**: A two-year study. Full weather station to measure rainfall and evaporative demand.

**Soil water**: Soil wetness monitored over the depth of the unsaturated profile, using gypsum block tensiometers, read manually, or soil salinity sensors. Periodic soil sampling provided salinity and other chemical information, and was used with soil water data to determine vertical water fluxes by the chloride balance modelling.

**Groundwater**: Groundwater monitored manually, using differential pressure sensors in 4 m deep, piezometer wells.

**Tree water use & growth**: Tree growth measured every six months. Sap flow in two sample trees of each of three species were measured using heat pulse velocity sensors for three weeks at a time. Results were scaled up to plantation water use.

**Results**: One of the three trees tested, total water use of Acacia nilotica exceeded rainfall (2225 and 1248 mm/yr at two sites), drawing from groundwater and causing a sharp drop in groundwater levels, up to 1.7 m during one dry season. Tree water use at the second site was strongly suppressed by higher salinity groundwater. Groundwater was recharged during irrigation of surrounding farmland. A risk on salinisation of the root zone exists caused by strong water extraction by the trees.

Three international case studies using various tools are summarised below.

**CASE 2: Monitoring both groundwater levels and riparian vegetation’s response to changes in water table depth.**

**Location:** Bill Williams River, NW Arizona, USA.

**Situation:** Poplars, willows and tamarix trees growing along the river and thought to be dependent on the alluvial aquifer at 1 to 3 m below ground level.

**Study objective:** Growth and survival of saplings of three species of riparian trees was monitored over differently changing groundwater regimes, to assess tree response.

**Methods:** Over a two year period, groundwater dynamics and the response of *Populus fremontii*, *Salix gooddingii* and *Tamarix ramosissima* saplings were measured. Tree variables measured were wilting, chlorosis (discolouration indicating extreme stress) and apparent shoot mortality. Groundwater depth below surface in sandpoint wells was monitored each month, by hand at each site.

**Results:** On a site of shallower groundwater but where the water table dropped most, 1.1 m in one year, more than 92% of willow and poplar saplings died, but Tamarix mortality was only 13% or less. At a site with deeper water tables and a lesser change in depth over the year, there was less mortality of poplar and willow, and greater stem growth.

Plant response to water table changes related to groundwater history, the plant’s physiology and morphology, soil conditions, supplementary rainfall and age. An understanding of these influences will allow conservation of riparian communities whilst exploiting groundwater.

**Reference:** Shafroth et al., (2000)

**CASE 3: Use of stable isotopes of water to indicate the use of groundwater by terrestrial vegetation. This is a commonly used technique, and this case illustrates its successful application in South Africa.**

**Location:** Forestry plantations in South Africa; both on the Mpumalanga escarpment and Zululand coastal plain.

**Study objective:** To test whether trees in fast growing timber plantations had access to deep groundwater (saturated zone water).

**Methods:** Samples of groundwater, soil water and surface water (ponds or streams) were taken to test that the groundwater had a distinct signature from unsaturated zone (soil) water. Sapwood samples were taken from plantation trees at known heights above groundwater. The isotopic signature of the water in the sapwood was measured to determine its source as either groundwater, soil water or a mixture of both.

**Results:** Tree roots were drawing groundwater in most cases, from depths as great 15 m in the case of *Eucalyptus grandis*, and from 4 m below ground in the case of *Pinus elliottii*. This was a pilot study, and the contrast between groundwater and soil water was not always adequate for the source of water to be identified, and there were site specific differences in tree rooting.

**Reference:** Midgley et al., 1994
SECTION 3 – FIELD STUDIES
FIELD STUDY A:
KAMMANASSIE NATURE RESERVE
A1. INTRODUCTION

This site was selected as there is currently controversy around the impacts of large scale groundwater abstraction on groundwater dependant vegetation, particularly the high altitude seeps and the springs which are the main source of the perennial water required by the endangered Mountain Zebra (Equus zebra zebra).

A2. SITE DESCRIPTION

Located about 20 kilometres to the east of Oudtshoorn in the far east of the Western Cape, the Kammanassie nature reserve is based around a small mountain range situated between the Swartberg and the Outeniqua mountains.

The nature reserve extends from 800 to 1,900m above sea level; most of the areas are between 900 and 1,500m. The highest peak is Mannetjies Berg (1,955m) (Richardson, et al., 1994).

On the lower northern slopes January maxima and minima are 39°C and 7°C respectively while in July they are 24°C and -3°C. On the upper slopes the corresponding values are 32 and 2°C (January) and 18 and -3°C (July) (Richardson, et al., 1994).
The geology is dominated by an upper (Nardouw) and lower (Peninsula) Cape sandstone formation separated by the Cedarberg shale band. There is a relatively high proportion of fine sand in the sandstones giving the soils a relatively high nutrient content and water holding capacity (Richardson, et al., 1994).

The sandstones are heavily folded and fractured and there are major fault zones which form the valleys for the major rivers. The fractures and the fault zones are believed to transmit large volumes of groundwater.

Rainfall is strongly influenced by orographic effects; northern slopes are in a rain shadow. The rainfall is bimodal with peaks in autumn and spring and ranges from 300 mm/yr\(^1\) on the lower north-facing slopes to 700mm/yr\(^1\) or more on the crest, (Richardson, et al., 1994).

Groundwater dependent vegetation is thought to occur in fault controlled riparian zones and at seeps and springs which are situated at various locations, particularly on the contact between the shale band and the sandstones. Groundwater fed baseflow to the river is thought to be significant.

**A3. Approach**

The aim of this first phase of the study was to determine the applicability of a combined remote sensing and Geographic Information Systems (GIS) methodology for assessing vegetation / groundwater interaction. The intention is to create a generic process that can be repeated by catchment management agencies using data relevant to their own catchment / water management area.

To undertake such a study, spatial data must be both found and/or generated so that analyses can be performed. Archives were searched and a base set of spatial data was built. Addendum A1 features a list of spatial data sets and their sources. All data was stored in ArcGIS\(^1\) data formats\(^2\).

Due to high costs involved in purchasing a license for use of 1:250 000 scale Council for Geoscience geological data, the decision was taken to capture a new set of lineament data. Two hydrogeologists, working independently, highlighted the linear features on hardcopy spacemaps\(^3\) of the satellite imagery. These features were digitised using a standard digitising tablet and ArcInfo GIS software\(^4\).

The lineaments were merged into one dataset and compared qualitatively. Duplicate lines were removed and a final lineament dataset was generated. See Figure A5 for final lineament map.

Spatial analyses were performed using the collected spatial data to assess the contribution of the lineaments to the interaction between groundwater and vegetation.

The 1:1 million scale geological spatial data was converted from vector format to a raster Grid using Spatial Analyst and added to the spatial database.

This layer was included in the spatial analyses as the different lithological units will have different potential permeability and ductility. The potential permeability will impact on the recharge of groundwater and the ductility will determine the width of the fracture zone around a lineament. The predominant lithologies are quartzites and shales.

---


2 ArcInfo coverages, ArcView shapefiles, and ArcGrids

3 Spacemap – an image map featuring satellite data at a specified scale, often matching existing topographic maps.

4 ArcInfo GIS – part of the ArcGIS suite of software, (see footnote 3).
Ductile shales will produce narrow fracture zones during lineament formation whereas quartzites are relatively ‘brittle’ producing wider, more fractured zones. The lithological units were classified according to their likely permeability (primary and secondary).

Satellite imagery archives were searched on the Internet to ascertain what imagery was available for the proposed study site. A list of these searchable archives can be found in Appendix A2. The suitability of the imagery was assessed on several criteria:

- **Availability** – data existence
- **Spectral characteristics** – what optical (or otherwise) measurements does the sensor make that are relevant to groundwater dependent vegetation?
- **Spatial characteristics** – at what ground resolution does the sensor measure.
- **Cost** – how much does the data cost?

The types of data that are most applicable for this kind of study are:

- ASTER – mounted on the Terra satellite platform
- Landsat 7 ETM+ (Enhanced Thematic Mapper+)
- SPOT4 Xsi

The availability of imagery depends upon several factors, the most important of which is often cloud cover. Obtaining cloud-free imagery of the study area is often one of the greatest problems facing many remote sensing projects.

It must be ensured that the spectral and spatial characteristics of a sensor suit the application. In this case a sensor that is capable of determining vegetation cover is required, i.e. the sensor must be able to detect high contrast between red and near infrared energy reflected from the surface as this changing highlights levels of chlorophyll in vegetation.

Groundwater dependant ecosystems are likely to be associated with lineaments and alluvium in this environment. These are not spatially extensive therefore high spatial resolution data will be required to detect their presence.

In this case the study area is relatively small, but as a rule, as ground resolution of satellite imagery improves, image extents reduce. Hence, for a larger study area, a larger number of scenes would be required.

Also, study areas often transcend satellite paths, therefore two overlapping images will be required (usually on different dates) from adjacent paths.

The satellite imagery is used to generate a vegetation index. This calculation is based around the difference between the near infrared and red reflectance recorded by the sensor.

The Normalised Difference Vegetation Index (NDVI) was calculated as part of this study using ERDAS Imagine 8.4 image processing software.

The standard NDVI equation is:

\[
\text{NDVI} = \frac{\text{Near Infrared} - \text{Red}}{\text{Near Infrared} + \text{Red}} \quad \text{Equation A1}
\]

(Adapted from Lillesand, et al., 1994)

The NDVI image consists of values ranging from -1 to +1. -1 representing low levels of vegetation and +1 high.
To better understand the role that geological structure plays in the study area, lineament density and connectivity indices were generated with the simple density function in the Spatial Analyst extension. Lineament density will assist in understanding the degree of fracturing that has taken place in the area. The connectivity will illustrate how interconnected lineaments are and give an indication of macro-porosity, i.e., to what extent could water flow from one lineament to the next? In the case of lineament density, the lineaments themselves were used as inputs to the density equation and for connectivity a digitised set of intersection points were used.

The outputs of the density calculations are raster Grids. These Grids are classified with weightings (see section 3 - weightings), higher near to high-density zones and lower in the low-density areas.

For the purposes of converting the NDVI image to a GRID for inclusion in the following analysis, the NDVI image had to be converted to an 8-bit image. This entails the stretching of the -1 to +1 data to a 0 - 255 range. This range is then classified according to its relative importance. High levels of vegetation are given a high importance and drier, sparsely vegetated areas are given a low importance. Generally speaking, NDVI is a relative index, which requires ground-truthing for calibration, but in this case, it was used as an indicator, hence no field validation was performed.

Using the classified NDVI, geology, lineament density map, and lineament connectivity a series of overlay calculations were performed using the Raster Calculator in Spatial Analyst.

The result of this set of spatial calculations is then rescaled to fit a range 1 - 10. This rescaled GRID is the end product of the analysis. It will be referred to as the Vegetation/Lineament Correlation (VLC) layer.

This layer will indicate areas of relatively lush vegetation associated with lineaments. It is inferred that this is a zone of interaction with groundwater.

### A4. Site Specific Approach

The satellite imagery chosen for this project was ASTER data, scene reference PR-180000_2000110702_009_011, captured 12 - 12 - 2001 which is mid-dry season. This was mainly due to its availability. ASTER data can be downloaded free of charge from EDC Land DAAC as part of their Earth Resources Remote Sensing programme. It is spectral equivalent (in the area of the electro-magnetic spectrum required here) to Landsat ETM+/TM data. The sensor is currently only capturing data on demand from science teams around the globe that are registered with USGS/NASA. Hence, the archive only contains these requested areas and areas captured during testing. Fortuitously, the Kammanassie Nature Reserve site falls within such an image.

The standardised NDVI index was altered in the ERDAS Imagine model making extension to take into account the different image structure as the standard model is set up to process Landsat TM imagery. In this instance, Bands 2 and 3 were substituted for Landsat TM bands 3 and 4. The table below show the comparison between Landsat TM and ASTER VNIR spectral characteristics.

<table>
<thead>
<tr>
<th></th>
<th>Band</th>
<th>Landsat 7 ETM+ (nm)</th>
<th>ASTER (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blue</td>
<td>1</td>
<td>0.45 - 0.52</td>
<td>0.52 - 0.60</td>
</tr>
<tr>
<td>Green</td>
<td>2</td>
<td>0.52 - 0.60</td>
<td>0.52 - 0.60</td>
</tr>
<tr>
<td>Red</td>
<td>3</td>
<td>0.63 - 0.69</td>
<td>0.63 - 0.69</td>
</tr>
<tr>
<td>Very Near Infrared</td>
<td>4</td>
<td>0.76 - 0.90</td>
<td>0.76 - 0.86</td>
</tr>
</tbody>
</table>

5 EDC Land DAAC - Eros Data Center Land Distributed Active Archive Center, USGS Land oriented Data Center, located at Sioux Falls, South Dakota, USA.
As can be seen from this table, the band comparison is almost identical with only the VNIR band of Landsat ETM/TM being 0.04μm wider.

Hence, instead of the usual equation:

\[
\text{NDVI} = \frac{\text{Band 4} - \text{Band 3}}{\text{Band 4} + \text{Band 3}}
\]

Equation A2

It will now read:

\[
\text{NDVI} = \frac{\text{Band 3} - \text{Band 2}}{\text{Band 3} + \text{Band 2}}
\]

Equation A3

The lineament density and connectivity Grids were generated using a search radius of 250 metres and a 50m cell size.

To perform the spatial calculation resulting in the interaction layer, the following ratings were applied to the individual layers. These weights were developed within the project team in order to draw the data into a common framework.

Weightings

<table>
<thead>
<tr>
<th>NDVI (no units)</th>
<th>Geology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original values</td>
<td>Weighting</td>
</tr>
<tr>
<td>0 - 120</td>
<td>0</td>
</tr>
<tr>
<td>120 - 150</td>
<td>0</td>
</tr>
<tr>
<td>150 - 170</td>
<td>5</td>
</tr>
<tr>
<td>170 - 230</td>
<td>10</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Lineament Density (per 50m cell)</th>
<th>Lineament Connectivity (per 50m cell)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Original values</td>
<td>Weighting</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0 - 1.5</td>
<td>3</td>
</tr>
<tr>
<td>1.5 - 3</td>
<td>6</td>
</tr>
<tr>
<td>3 - 5</td>
<td>10</td>
</tr>
</tbody>
</table>

As the lineament data set for the study area did not feature a great deal of connectivity the lineament Connectivity layer was removed from the spatial calculation as it was seen to bias the results.

### Assumptions

- Structural linear features, as opposed to primary bedding features, have been identified. Groundwater may also occur at a shallow level at lithological contrasts associated with bedding.
- Likely structural extensions of lineaments have not been inferred, only the actual structural features which are visibly distinctive at the land surface. Inferring non-visible extension would increase lineament density and connectivity.
- Groundwater dependent vegetation is only associated with lineaments. Other groundwater dependent vegetation may occur in the area, especially associated with alluvial aquifers.
A6. Results

Figure A2, below, is rose diagram of lineament orientation length and frequency, this was generated using the ArcView GeoTools extension (see Appendix B for URL).

Lineament summary statistics
- A total of 211 lineaments were digitised in the study area taken from the combined manual interpretations by the 2 geologists.
- The minimum length was 119m and the maximum was 7728m.
- The total length of lineaments captured was 194737m with a mean average length of 923m.

Maps of lineaments, lineament density and lineament connectivity can be seen in Addendum A4. These are based viewed in colour and are available electronically from the CSIR, Cape Water Programme. Below is a list of the Figures showing the separate analyses outputs:

- Figure A4 - ASTER data false colour composite of the study area
- Figure A5 - Digitised geological lineaments
- Figure A6 - Lineament Density Index
- Figure A7 - Lineament Connectivity Index
- Figure A8 - NDVI image
- Figure A9 - Classified NDVI
- Figure A10 - Classified Lithology
- Figure A11 - Vegetation Lineament Correlation (VLC).
Figure A3 below shows the range of values and summary statistics for the NDVI image.

**Summary Statistics**
- Minimum = -0.23
- Maximum = 0.81
- Mean = 0.31
- Standard Deviation = 0.093

![Histogram of NDVI values](image)

*Figure A3: Histogram of NDVI values.*

The results of the ASTER NDVI can be seen in Figure A8.

The ASTER false colour composite image clearly shows the relatively lush vegetation in mid-December, associated with quaternary rivers, irrigated areas and some lineaments. The white areas represent bare soil on agricultural land and alluvium.

Figure A11 is the VLC map. From this it is possible to see the distribution of higher values and their coincidence with the major linear features. The most prominent areas are those along the Vermaaaksrivier and Moolenaar rivier valleys.

**A7. DISCUSSION OF PROCESS**

The process for carrying out this analysis is outlined in Figure A5 in Addendum A3. Some alterations to the process could enhance the study, such as using a vegetation change process, i.e. performing change detection between wet and dry season image and using this as a vegetation input to the spatial calculation. The main drawback to this is obtaining wet season imagery, as high precipitation is usually coincident with high cloud cover. Also, high resolution geological information will enhance the accuracy of the calculation as the coverage used is coarse.
To gain higher benefit from a lineament connectivity layer in further studies it would be preferable to join segments of lineaments with inferred sections where possible. This would result in more intersections, a better understanding of non-visible connectivity and hence a more complete picture of groundwater / vegetation interactions in the study area in question.

A8. Summary of necessary capacity

The capacity required to perform these tasks is outlined below.

**GIS data collection and collation**

**Skills**: skills required for this are minimal. However, a network and knowledge of spatial data providers and sources is essential.

**Hardware**: Standard – High-end PC workstation. Complex spatial analysis and processing will be quicker with a dual processor.

**Software**: Minimum – ArcView 3.2 (or equivalent) Desktop GIS with Spatial Analyst extension.

**Satellite data search**

**Skills**: As this is a simple process of using search facilities on Internet pages, the capacity required is minimal. The search facilities are usually accompanied by good help facilities and tutorials to assist the user with the process. The EDC Land DAAC search help is extremely extensive and help and information can be obtained at any stage. This site also features exhaustive glossaries, definitions and metadata.

**Hardware**: a basic PC with a connection to the Internet, faster connection speeds will only improved/enhance the process. As a user is interacting directly with the provider databases, generally in USA and Europe, working outside of high Internet usage times will speed the process up. This is usually before 13.00 (CET), before the first time zone of the USA comes online.

**Software**: Microsoft Internet Explorer 5 (or greater), Netscape 4.7 (or greater)

**Satellite image processing**

**Skills**: Operator skill levels required to perform these tasks are intermediate with some exposure to remote sensing theory being of benefit.

**Hardware**: Standard – High-end PC workstation. Complex image processing will be quicker with a dual processor.

**Software**: The techniques used here are standard processes and tools to carry out these routines can be found in most remote sensing image processing software packages. In this case Erdas Imagine 8.4 was used to perform most of the image processing tasks. The NDVI was calculated using Erdas Imagine model maker. Imagine comes with standard Landsat and SPOT NDVI equations built in, but the model had to be adapted to operate with ASTER data.

The initial Geocoding of the satellite data was achieved using the georeferencing and resampling tools of Erdas Imagine. If Landsat or SPOT data are used, these products can be purchased pre-geocoded.
If one is using ASTER data, the data is delivered in HDF-EOS format, which requires a converter so that it can be used with standard GIS and remote sensing software. Such a tool can either be downloaded from http://hdfeos.gsfc.nasa.gov/hdfeos/SoftwareDist.html. Alternatively, a commercial converter can be purchased from PCI Geomatics. In this case PCI Geomatica Gateway was used to transform the data from HDF-EOS into Erdas Imagine img format.

**GIS data manipulation and spatial analysis**

- **Skills**: The GIS analyses performed in this project are intermediate level tasks that will require a reasonable amount of exposure to GIS software and techniques. Modern GIS packages have extensive help and tutorial facilities that explain in detail how to perform specific tasks and often include information on the theory of a process.

- **Hardware**: Standard – High-end PC workstation. Complex spatial analysis and processing will be quicker with a dual processor.

- **Software**: Minimum – ArcView 3.2 (or equivalent) Desktop GIS with Spatial Analyst extension.

### A9. CONCLUSIONS

This study applied best available (and affordable) remote sensing technology to assess the potential occurrence of TGDEs in a fractured rock terrain. Probable locations were indicated based on correlation of known groundwater bearing structures (lineaments) and the occurrence of relatively lush vegetation. The dependence of these areas is being ground-truthed by WCNCB who are currently monitoring moisture stress and plant vigor in an area potentially impacted by pumping.

### A10. FURTHER WORK

The Water Research Commission is funding a study of the environmental impacts of groundwater abstraction in the Kammanassie Nature Reserve (Project No K5/1115). The aim of that project is to determine the impacts of groundwater abstraction by the Vermaak’s River water supply scheme on: riparian vegetation, terrestrial vegetation, springs, aquatic ecosystems and the Cape Mountain Zebra and other fauna. The study was motivated by concern about the impacts of both the current abstraction and the proposed increase in abstraction by this scheme. A number of aspects are being studied to obtain the data needed to address the objective:

- **Water stress**: a combination of leaf transpiration, measured with a porometer, and plant moisture stress measured with a pressure chamber. The plant species being measured are: Acacia karoo, Osyris compressa and Nymannia capensis. These tests are supplemented with measurements of the water content of the leaves. An automatic weather station is being used to gather data on rainfall, temperature, solar radiation and relative humidity. A visual assessment of the plant stress is also being made.

- **Botanical surveys** to identify the different plant communities in the area and to quantify their composition and structure.

- **Monitoring of springs** in the area for flow rates and chlorides. The site is photographed and general ecological information is recorded, including observations or evidence of utilisation by the Cape Mountain Zebra.

- **SASS5 surveys** are being done of the streams downstream from the springs as the survey technique is not appropriate for the springs themselves. Samples of the aquatic fauna are being sent to the appropriate authorities for identification and curation.

- **A hydrocensus** to estimate the amount of groundwater being abstracted by farmers in the area.
This project could complement the above work by using satellite data to quantify the extent of the likely groundwater dependent ecosystems in the Kammanassie area and relate that to the occurrence of springs. The botanical communities identified in the existing study can also be used in ground-truthing the satellite data. There is also an opportunity to compare the whole-tree transpiration estimates using sapflow techniques with the measurements at the leaf-level being done in the existing Kammanassie study. It may also be possible to use carbon isotopes in the wood of Acacia karoo to get a longer-term picture of moisture stress and an indication of the impacts of the recent dry drought years on plant moisture stress.
ADDENDUM A1

SPATIAL DATA

<table>
<thead>
<tr>
<th>Name</th>
<th>Scale</th>
<th>Source</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rivers</td>
<td>1:50 000</td>
<td>Surveyor General</td>
</tr>
<tr>
<td>Quaternary Catchments</td>
<td>1:1 000 000</td>
<td>WRM90</td>
</tr>
<tr>
<td>Roads</td>
<td>1:1 000 000</td>
<td>Surveyor General</td>
</tr>
<tr>
<td>Geological Lineament</td>
<td>1:50 000</td>
<td>CSIR</td>
</tr>
<tr>
<td>Geology</td>
<td>1:1 000 000</td>
<td>Council for Geoscience</td>
</tr>
<tr>
<td>Imagery</td>
<td></td>
<td></td>
</tr>
<tr>
<td>ASTER image</td>
<td></td>
<td>USGS EROS Data Centre</td>
</tr>
<tr>
<td>PR-180000_2000110702_009_011</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Captured 12 - 12 - 2001</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

ADDENDUM A2

SATELLITE ARCHIVES

Several sources of data are available through a web interface.

SPOT  www.sac.co.za

Landsat 7 and ASTER -  http://edcimswww.cr.usgs.gov/pub/imswelcome/

These sources often inform the decision regarding which sensor to choose for the project.

GIS links


ESRI –  http://www.esri.com
Addendum A3

Detailed Process Diagram

Figure A5
ADDENDUM A4

SUPPORTING FIGURES

Figure A4 ASTER data false colour composite

Legend:
- Study site
- Quaternary catchments
- RGB Composite
- Green: Layer_2
- Red: Layer_3
- Blue: Layer_1

Kilometres

Figure A6 Geological Lineament Density

Legend:
- Lineament trend
- Customary catchments
- Lineament Density Index
- Rivers
- Study area

Kilometres
Figure A9 - Classified NDVI
FIELD STUDY B:

ATLANTIS
B1. INTRODUCTION

The Atlantis study area was chosen because the indigenous dune vegetation may be dependent on groundwater and the aquifer has been studied and monitored for more than 20 years. The two study sites were chosen to provide information on the comparative water-use of the indigenous vegetation and an invasive Australian wattle species (Acacia cyclops) under similar conditions. Previous studies at the site have found that recharge under the vegetation was lower than under the open sand (Fleischer and Eskes, 1992) but impacts of the indigenous and exotic vegetation have not been compared.

The relatively flat topography and the availability of sufficiently large areas of relatively uniform vegetation provided an opportunity to use the Bowen Ration technique to measure plant water-use (see Section 2). There also is an excellent database on the rainfall and the aquifer with records of water levels and groundwater abstraction which extend back for about 20 years.

An important consideration in choosing the study area was the risk of theft of the equipment. Although the reserve is open to the public, it has low visitor numbers. Therefore, it provided a relatively well-protected environment and minimised the risk of the loss of the very expensive measuring equipment. The current replacement cost of the complete station would be in excess of R100,000.

Two students from the Botany Department at UWC were contracted to do a vegetation survey of the study sites and provide data needed for modelling the evaporation from the vegetation. This study complemented a separate CSIR funded project which was aimed at developing the skills and experience of CSIR staff in setting up, maintaining the measuring equipment and analysing the resulting data.

B2. THE BOWEN RATIO TECHNIQUE

This section gives a brief description of the Bowen Ration technique, more details are given by Savage et al., (1997). The technique estimates the energy balance at a site and uses this to calculate evaporation. Many people are familiar with the idea of the water balance, which in its simple form is represented by the following equation:

\[
\text{Rainfall} = \text{total evaporation} \pm \text{change in soil and groundwater storage of water}
\]

The total evaporation component can be further broken down into:

\[
\text{Total evaporation} = \text{plant transpiration} + \text{interception} + \text{soil evaporation}
\]

Transpiration is the water lost as vapour through stomata (pores) in its leaves; interception is rainwater which is intercepted by the surface of the plants leaves and branches or litter and evaporated directly back to the atmosphere; and soil evaporation is water lost directly from the soil surface.

The units in the equations above are units of water but, because energy is required to drive evaporation (i.e. turn water from a liquid state into vapour), there are equivalent relationships which use energy as the units. As water evaporates from a surface it releases energy, cooling that surface. The energy that is released during the cooling is called latent (hidden) heat because it does not heat the air as such but is “stored” in the vapour, only being released when the vapour condenses. Energy that goes into heating the air or the soil is called sensible heat to distinguish it from latent heat. If the right components of the energy flows or fluxes are measured, then evaporation can be estimated from the energy (heat) fluxes. The energy fluxes are
estimated from measurements of the:

- profile of vapour pressure and temperature of the air between two fixed heights above the vegetation canopy;
- net radiation which is the difference between the radiation from the sun and the radiation reflected back into the atmosphere from the vegetation and soil; and the
- soil heat (energy) flux and moisture content.

These measurements are used to estimate the total evaporation and separate it into soil evaporation and plant-derived evaporation (primarily transpiration) using the formulas described in the methods section.

---

### B3. **BACKGROUND INFORMATION**

#### B3.1 Location

The study site is situated in the Koeberg Nature Reserve (18° 26' E, 33° 41' S), about 30 km north of Cape Town on the west coast. The reserve is situated on land owned by Eskom and is regarded as a critical conservation area and a key part of the proposed West Coast Biosphere Reserve (CMC, 2000, Heijnis et al., 1999; Maze and Rebelo, 1999). It provides protection to a variety of vegetation types and landscape features, eight rare plant species, six rare bird species and one rare invertebrate species. The animal life is moderately species rich with a variety of small mammals, none of which are dependent on surface water.

#### B3.2 History

Historically, the study area was known as Duynefontein and several springs are indicated on the map of 1790 (Heineken, 1987). The perennial Silwerstroom stream, which is maintained by groundwater discharge, was probably an important water source for the original Khoi pastoralists who used the coastal areas. Formal fanning in the area dates from the mid-1700s (Baynes, 1984). The sandy soils are unsuitable for cultivation so the impact of fanning was limited to grazing of livestock with patch burning and cutting of the strandveld to enhance the cover of the more palatable herbs and grasses. The sand plume that begins north of the Koeberg power station probably extended right through the study area to the Witsand dune field east of the coastal road. Dune reclamation work resulted in the invasion of the vegetation on the margins of the sand fields and the steady colonisation of the sands (see also the section on invading alien plants).

#### B3.3 Climate

The climate is Mediterranean with most of the rain falling during the winter half-year. The mean maximum temperature is 23.2°C and the mean minimum is 11.8°C (Zhang et al., in prep.) and the temperatures are strongly moderated by the proximity to the Atlantic Ocean. The annual rainfall at a station about 2 km north-east of the study area averaged 413.8 mm during the period, 1988-1998, ranging from about 320-530 mm, very similar to that at Atlantis town (Figure B1). Fogs occur regularly throughout the year and are most frequent during the winter months. Most of the rainfall occurs during the winter but there is still an appreciable amount of rainfall in the summer months (Figure B2). The deviations from the monthly means show the unusually dry summers that have been a feature of the last few summers, particularly those of, 1999 and 2000 (Figure B3).

The prevailing wind direction is due south to south-east, especially during the dry summer months, with winter rainstorms being associated with north-west and south-west winds (Heineken, 1987). The dry and strong south-easterly winds are associated with hot, dry conditions and low humidities (high vapour pressure deficits).
Figure B1: Annual rainfall measured at Atlantis, about 10 km northwest of the study site.

Figure B2: Mean monthly rainfall at Atlantis town for the period shown in Figure B1.
The Atlantis aquifer is situated in the deep Quaternary deposits of generally unconsolidated quartzitic sands (Bredasdorp and Varswater Formations) which overlie the bedrock of the Malmesbury formation (Cave et al., 1996). The main body aquifer is partially overlain by the Langebaan limestones which are exposed on the surface in places. The aquifer is unconfined and contains a number of groundwater compartments which differ in the quality of the water (Cave et al., 1996). The study site is situated in the Witzand compartment near the Witzand wellfield where water is abstracted for use in the town of Atlantis. The potential yield of this wetfield is about 5.4 million m$^3$ per year with, 1995 abstraction being 3.3 million m$^3$. Recharge through the coastal artificial recharge basins has raised water levels up to 1 km inland, which is close to the study site. Eskom also abstract groundwater in this area for use at the Koeberg nuclear power station.

This aquifer has been well studied by the CSIR for groundwater management purposes, including management of abstraction and artificial recharge (Zhang et al., in prep.). A summary of the development of groundwater abstraction in the area is given in Table B1. Abstraction in the Witzand wellfield is relatively recent but it now yields the bulk of the water. Concern about the degree of drawdown led to a decrease in the abstraction and a resting period during the summers of, 1998 and, 1999 (Zhang et al., in prep.).

The water table is normally 4-7 mbgl and the aquifer has a maximum saturated thickness of 35 m (Cave et al., 1996). Aquifer permeability is around 20 m/day. Recharge was estimated from hydrograph studies to be 13-30% of the rainfall (Fleischer and Eskes, 1992). Chloride studies estimated recharge in vegetated areas to be 25% compared with 42% (30-60) in the bare sand dunes.
Table B1: Major events in the development of the water management scheme at Atlantis

<table>
<thead>
<tr>
<th>Year</th>
<th>Event</th>
</tr>
</thead>
<tbody>
<tr>
<td>1972</td>
<td>First hydrogeological investigations in the Atlantis area - Geological Survey</td>
</tr>
<tr>
<td>1974-1980</td>
<td>Drilling of exploration and production boreholes - Dept. of Water Affairs</td>
</tr>
<tr>
<td>1976</td>
<td>Initial water supply from Silwerstroom springs</td>
</tr>
<tr>
<td>1982</td>
<td>Production begins at Witzand wellfield</td>
</tr>
<tr>
<td>1983</td>
<td>Nine new production boreholes commissioned at Witzand wellfield</td>
</tr>
<tr>
<td>1985</td>
<td>Regular monitoring of groundwater levels begins</td>
</tr>
<tr>
<td>1988</td>
<td>Initial filling of primary coastal recharge basin</td>
</tr>
<tr>
<td>1989</td>
<td>Eight new production boreholes drilled</td>
</tr>
<tr>
<td>1993</td>
<td>Twelve new production boreholes drilled</td>
</tr>
<tr>
<td>1994</td>
<td>Seven new production boreholes constructed</td>
</tr>
<tr>
<td>1994</td>
<td>Environmental Impact Assessment undertaken for Witzand Farm - Knight Hall Hendry</td>
</tr>
<tr>
<td>1996</td>
<td>Seven new and replacement production boreholes drilled</td>
</tr>
<tr>
<td>1998</td>
<td>Construction of surface water pipeline to bring surplus water from Melkbosstrand</td>
</tr>
<tr>
<td>1999</td>
<td>Wellfield shutdown: Silwerstroom July - November; Witzand September – December</td>
</tr>
</tbody>
</table>

During the calibration of one groundwater model for the aquifer the annual recharge was estimated to be 9-44 mm per year (Du Toit, 1997), while a second model calibration gave 4.4-16.8% of the annual rainfall or 18-69 mm per year, with the highest values being in the open dune areas (Zhang et al, in prep.). It is expected that recharge beneath the dense stands of vigorous, invading acacias will be lower than under fynbos or strandveld, but this has not been measured. In a highly managed aquifer such as this it is obviously also important to manage land use (vegetation) because of its influence on groundwater replenishment.

A WRC study on the impact of agricultural activities on groundwater quality in the Atlantis area noted a significant seasonal variation in a control area with a high cover of Acacia saligna, a nitrogen fixing species (Colvin, 1997). The nitrate peak following groundwater recharge was greater in the control area at 17 mg/L than in a fodder crop field where sewage sludge was applied as a soil conditioner (15mg/L). Nitrogen isotope analyses confirmed that there were different sources of the nitrate in the groundwater, namely natural soil biota and vegetation for the control area, and sewage sludge in the field. The acacias were infected with a rust fungus and dying off in the control area, providing a significant biomass source with little or no nitrate uptake from the sandy soil.

B3.5 Vegetation

B3.5.1 Indigenous communities

There are two main types of vegetation on the deep Quaternary sand deposits of the West Coast dune thicket (also known as strandveld) and fynbos (Boucher, 1981a, 1983; Boucher and Le Roux, 1993; Daines and Low, 1993, Heijnis et al., 1999). Dune thicket is found primarily on alkaline (calcareous i.e. lime-rich) sandy soils, and fynbos on the acidic sandy soils derived from sandstones and granites and acidic dune sands. It is an open to dense, vegetation, dominated by large evergreen shrubs - scrub including large shrubs such as Euclera racemosa, Olea exasperata and Rhus species and low shrubs (Boucher and Le Roux, 1993). The understorey is dominated by herbaceous species (grasses, geophytes, annuals) which are dormant in the summer. Shrubs are generally dominant where the soils are well-drained and herbs, grasses and sedges where the water-table is shallow, either seasonally or permanently.

The vegetation on the study site was described as West Coast Dune Thicket - Lowland Fynbos transition (Boucher, 1987; Heineken, 1987). This is characterised by a relatively open canopy and the occurrence of a tall, tufted restio (thatching reed Wildenowia incurvata). The presence of the restio is an indication that the sands are relatively low in lime (calcium).
A survey of the coastal vegetation at Silwerstroom (about 5 km north of the study area), identified three different communities associated with surface water: reed swamp (Phragmites or Typha) associated with organic (peat) soil (perennial surface or near-surface water); sedge (Juncus) marsh on sand (seasonally inundated); and channel fringing scrub adjacent to flowing water and on the landward margin of the swamp or marsh vegetation (Boucher and Parsons, 1980; Boucher in Heineken, 1987). The channel fringing scrub includes tall shrubs of Psoralea pinnata (P. aphylla), a species which is apparently sensitive to water-level fluctuations (Bayne, 1984). No wetland vegetation was observed in the vicinity of the study sites themselves although there is a marshy area in a dune swale about 1 km north of the strandveld study site.

Dr C Boucher (footnote in Heineken and Nicholson, 1984) reports that a local farmer Mr Duckitt had informed him that the flora was already suffering from the water extraction process. No further details on the nature of the stress were given. A field inspection of the Silwerstroom area in, 1984 found no evidence that groundwater abstraction had any effect on the vegetation except in the riverine scrub (Bayne, 1984). A number of the dominant shrub species (Olea, Rhus, Euclea) are known to be deep rooted (Le Maitre et al., 1999) and could be using groundwater at depths of 10 m or more below the surface. They may also be moistening the surface layers through hydraulic lift (Richards and Caldwell, 1987; Caldwell et al., 1998) but this still needs to be investigated.

Very little is known about the fire ecology and dynamics of strandveld, although there are records of fires burning strandveld (Boucher, 1981a). The dominant shrubs all resprout readily from their stems and rootstocks and the other species recover from seeds or by sprouting, but the vegetation does not require fire to maintain it in a healthy condition.

B3.5.2 Invading alien plants

No records have been found of the introduction of alien (introduced) species to the Koeberg area itself. The Forestry Department had a policy of actively reclaiming all drift (wind blown) sand areas from its establishment in 1872 until the late, 1970s (Shaughnessy, 1980, 1986, Boucher, 1981b). It carried out large-scale reclamation work using acacia species (wattles) around Cape Town as well as actively promoting sand reclamation by private land owners. The department began reclamation work at Blaauwberg in about, 1908 using Marram grass (Shaughnessy, 1980). Acacia cyclops and A. saligna seeds were sown there in, 1924 and, 1925. The department continued to manage this area till the late, 1970s. The Divisional Council of the Cape was still involved in drift sand control in early, 1970s with ‘sand-fixing species’ (probably wattles) at Blaauwberg and Melkbos. It is likely that drift sand reclamation at Witsand and Duynefontein (as the Koeberg area was then called) began in the, 1920s or thirties and continued till the, 1970s. The invaded portion of the study area is dominated by Acacia cyclops (Rooikrans) with occasional A. saligna (Port Jackson).

The understory in the Rooikrans invaded areas generally is sparse or lacking except for localised patches, particularly those with shallow calcrete which are dominated by stands of the tall, tufted restios. The impacts of these invasions on groundwater losses are not known but dense invasions result in an increase in biomass and changes in nutrient pools and cycling (Versfeld and Van Wilgen, 1986; Richardson et al., 1992; Stock and Allsop, 1992). An increase in biomass is generally associated with an increase in evapotranspiration (Le Maitre et al., 1996) so it is likely that the invaded stands may intercept or transpire more water, reducing recharge.

B4. Study sites

Two study sites were chosen as shown in Figure B4. The approximate area over which evaporation would be measured, depending on the direction of the wind, is indicated by the circles which have a radius of 400 m. The centre of the circle is the approximate location of the micrometerological measure station itself and the vegetation sampling was done within the area of the circle.
The study area is situated in the coastal dune fields and is about 25-40 m above mean sea-level rising further inland to 100-300 m (Figure B5). Local relief is provided by the stabilised dunes which generally are about 5 m from crest to bottom. The two study sites differ in their local relief with the Thicket site having more gently sloping dunes (Figure B5). Rooikrans is known to invade be a vigorous invader along the margins of open sand areas so it is likely that that part of the area was originally open sand and thus has a greater relief.

Figure B4: A high resolution colour image (scale ±1:2000) showing the location of the study sites (400m radius circles) in the Koeberg Nature Reserve.

The N7 runs diagonally from the bottom right corner. The CMC Water Processing Plant weather is situated just out of the image to the north of N7 Atlantis road intersection. Recharge basins can be seen in the north-east corner of the image.

Figure B5: A map of the study sites showing the elevation and the differences in local relief.
### B5. METHODS

#### B5.1 Vegetation sampling

Ten 10m long transects were laid out randomly within a 400 m range of the micrometeorological measurement points. The location of each of the transects was determined using a Magellan 2000 hand held GPS. The GPS points were then plotted in MapInfo and converted to a shape file for use in ArcView.

A vegetation profile of each site was compiled for the large woody shrub species to show the height, structure of the canopy and distribution of the plants. One square metre quadrats were also laid out and the leaves were removed from the shrub canopies which covered those quadrats. The leaves were put in plastic bags to minimise moisture loss taken back to the laboratory at UWC where the leaf areas were determined using a LI-COR portable area meter, model LI-3000. The first sampling was carried out in April before the winter rains and the second sampling was in August after the rains. Spring is the beginning of the annual growth cycle of the Strandveld (Siegfried, 1981).

#### B5.2 Climate data

Climate data were obtained from Atlantis and the Cape Metropolitan Council and databases maintained by the CSIR. Long-term rainfall data for Koeberg Powerstation were supplied by Eskom.

#### B5.3 Measurement of water levels

Water levels are monitored at monthly or bimonthly intervals in monitoring boreholes situated in the Witzand wellfield and the adjacent areas (Figure B6). The abstraction and monitoring wells for the Koeberg nuclear power station are situated further south (Figure B7). The data from the monitoring wells in the Witzand wellfield are maintained in a database by the CSIR on behalf of the Cape Metropolitan Council. Records for certain of the monitoring wells were used to estimate the likely depth of the water tables within the study area.

<table>
<thead>
<tr>
<th>Monthly measurements:</th>
<th>Two-monthly:</th>
</tr>
</thead>
<tbody>
<tr>
<td>WP100</td>
<td>WP41</td>
</tr>
<tr>
<td>WP105</td>
<td>WP98</td>
</tr>
<tr>
<td>WP121</td>
<td>WP118</td>
</tr>
<tr>
<td>G33093</td>
<td>WP120</td>
</tr>
<tr>
<td>G33447</td>
<td>WP125</td>
</tr>
<tr>
<td>WP104</td>
<td>G33099</td>
</tr>
<tr>
<td>WP107</td>
<td>G33105</td>
</tr>
<tr>
<td>G32953</td>
<td>WP42</td>
</tr>
<tr>
<td>G33094</td>
<td>WP99</td>
</tr>
<tr>
<td>WP119</td>
<td>WP119</td>
</tr>
<tr>
<td>WP124</td>
<td>G33098</td>
</tr>
<tr>
<td>WP125</td>
<td>G33102</td>
</tr>
<tr>
<td>G33984</td>
<td>G33132</td>
</tr>
</tbody>
</table>

*Figure B6: Water level monitoring boreholes near vegetation study sites. And the monitoring frequency.*
B5.4 Measurement of evaporation

Evaporation was estimated using the Bowen Ratio technique (see Section 2) as described above. The components of the energy balance, soil water storage and general climatic conditions were monitored over the period 30 November 2000 to 1 September 2001, and measurements will continue until December 2001. The Bowen Ratio energy balance system, together with a complete automatic weather station, was moved between the two research sites at two weekly to monthly intervals. For most of the months, data were collected from both sites (Table B2). The soils were sampled to a depth of 0.90m to obtain information on the physical and other characteristics for calculating the moisture content.

Table B2: Months for which energy balance data were collected at the strandveld and rooikrans sites

<table>
<thead>
<tr>
<th></th>
<th>2000</th>
<th></th>
<th>2001</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Months</td>
<td>Nov</td>
<td>Dec</td>
<td>Jan</td>
<td>Feb</td>
</tr>
<tr>
<td>Strandveld</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Rooikrans</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The rainfall, solar radiation, air temperature, relative humidity, windspeed and wind direction sensors were installed together with the Bowen ratio energy balance system. The rainfall was measured with a tipping bucket rain gauge with a 0.2 mm resolution. The solar radiation was measured with a solarimeter and the air temperature and relative humidity with a Vaisala temperature and humidity probe (CS500). The windspeed and the wind direction were measured with a three-cup anemometer and a windvane.
The soil water content was monitored continuously, with water content reflectometers at 0.08m and 0.5 m below the soil surface, during the period that the Bowen ratio energy balance system was at that site. Additional soil samples were collected at the frequent visits, and the gravimetric and volumetric soil water contents were calculated. The volumetric soil water content (%) is the volume water per volume soil. The volumetric soil water contents can be misleading when comparing different soil layers because it does not take into account the characteristics of that specific layer. However, the effective degree of saturation of a specific soil layer does take the water retention characteristics into account. These characteristics determine the amount of water a soil can hold at a particular water potential.

### B5.4.1 Reference evaporation

The reference evaporation can be defined as the total evaporation above a short well-watered grass (reference) surface (Allen et al., 1998). The reference evaporation (E*o) was calculated with the Penman-Monteith equation, using the automatic weather station data recorded above the reference surface (Campbell, undated).

### B5.4.2 Total evaporation (ET)

#### B5.4.2.1 Estimation of total evaporation

Total evaporation was measured with the Bowen ratio energy balance technique at both the strandveld and rooikrans sites (Figure B8). This technique measures the components of the energy balance (energy fluxes) above a canopy

\[ Rn - G = \lambda E + H \]  \hspace{1cm} \text{(B.1)}

where \( Rn \) is the net radiation, \( G \) the soil heat flux density (energy heating the soil), \( \lambda E \) the latent heat flux density (energy driving evaporation) and \( H \) the sensible heat flux density (energy heating the air).

The latent heat flux density (\( \lambda E \)) was calculated as

\[ \lambda E = \frac{Rn - G}{\beta + 1} \]  \hspace{1cm} \text{(B.2)}

\[ \lambda E = \frac{\rho e K_v (e_1 - e_2)}{P(z_1 - z_2)} \]  \hspace{1cm} \text{(B.3)}

where \( \beta \) is the ratio between the sensible and latent heat flux densities, \( \lambda \) the latent heat of vaporization, \( \rho \) the density of the air, \( e \) molecular ratio, \( K_v \) the diffusion coefficient for latent heat transfer, \( P \) the atmospheric pressure and \( e_1 \) and \( e_2 \), the vapour pressure at height \( z_1 \) and \( z_2 \) respectively.

The accurate measurement of the water vapour pressure difference (\( e_1 - e_2 \) or \( \delta e \)) over a height (\( z_1 - z_2 \) or \( \delta z \)) is essential to the accurate calculation of the latent heat flux density and hence the total evaporation, ET

\[ ET = \frac{\lambda E \text{ timeconversion}}{\lambda} \]  \hspace{1cm} \text{(B.4)}

where timeconversion was used to convert \( \lambda E \) (Wm\(^{-2}\)) to ET in mm per time period. For more details on the Bowen Ratio energy balance technique see Savage et al., (1997).
B5.5 Soil water content, degree of saturation and soil water storage

Soil water content was measured at both the strandveld and rooikrans sites. The soil water content sensors (water content reflectometers) were installed and 0.08 m and 0.50 m below the soil surface. These sensors measured the infiltration of water into the soil, following a rainfall event and the drying of the soil, as a result of water uptake (transpiration) by the plants and soil evaporation. For more details of this technique see (Everson et al., 1998).

B5.5.1 Degree of saturation

The volumetric soil water content ($\theta_v$) measured with the water content reflectometers, were further converted into relative saturation values ($S_e$) (Van Dam et al., 1997)

$$S_e = \frac{\theta_v - \theta_R}{\theta_S - \theta_R}$$  \hspace{1cm} B.5

where $\theta_S$ is the saturated soil water content and $\theta_R$ the residual soil water content as derived from the water retention characteristics of the soil.

B5.5.2 Changes in the soil water storage

The soil water content sensors were used to cover the expected range of moisture conditions for the study site. Water retention curves ($\psi_m$ vs. $\theta_v$) were determined in the laboratory from undisturbed cores collected from the sites. These curves were used to convert matric potential to soil water content. These ‘spot’ soil water content values were subsequently converted into soil water storage values over a 0.1 m and 0.90 m layer and, finally, the 1.00 m profile. Changes in the soil water content were calculated over different periods

$$\Delta S = (S_{Initial} - S_{Final})$$  \hspace{1cm} B.6
or

\[ \Delta S_i = \Delta Z_i (\theta_{\text{final}} - \theta_{\text{initial}}) \]

where \( S_{\text{initial}} \) and \( S_{\text{final}} \) is the initial and final stored soil water, \( \Delta S \) is the change in the soil water content in layer \( i \), \( \Delta Z \) the thickness of the soil layer \( i \), and \( \theta_{\text{final}} \) and \( \theta_{\text{initial}} \) the final and initial volumetric soil water contents.

### B5.6 Tracer sampling

The project team plan to carry out tracer tests on the rooikrans and strandveld plants to confirm their use of groundwater.

### B5.7 Analysis of remote sensing data

A classification was done of a high-resolution, natural colour image which was supplied in a compressed (MrSid) format which cannot be spectrally analysed and classified. The compressed image was converted with the help of Mr. Sid Geoviewer to a TIFF format which can be used by various image classification packages. ERDAS was used to perform an unsupervised (i.e. automatic) classification on the study area.

We also propose to do a satellite (Landsat) image classification to complement the ground-based studies. These studies (see the text) have compared a rooikrans site with deep groundwater and a strandveld site with shallow groundwater. For the satellite analysis we will select two additional areas to complement this comparison by including rooikrans on shallow groundwater and strandveld on deep groundwater. We will then compare images from a wet season and a dry season to determine whether the seasonal differences in the different vegetation types can be related to the depth to groundwater.

### B6. Results

#### B6.1 Soil profiles

The soil profile at both the strandveld and rooikrans sites can be described as deep, non-red Namib form. This soil form consists of an orthic A horizon overlaying a regic sand horizon (Soil classification working group, 1991). The soil physical properties at the strandveld and rooikrans sites are very similar, with the medium and fine sand accounting for about 90% of the total soil (Table B3). The proportion of coarse sand differs between the two sites, with the rooikrans site having more coarse sand than the strandveld site at all three depths (Table B3).

The soil pH and electrical conductivities are shown in Figures B9 and B10 respectively. The soil pH’s at the strandveld site are lower than those at the rooikrans site, throughout the soil profile. The electrical conductivities at both sites are very low, and show the same trend as the pH values. The water retention characteristics reveal something about the amount of water (volumetric soil water content) that the soil can hold before becoming saturated (\( \theta_s \), the saturated soil water content), and the extent to which a soil can dry out, until no soil water is available for plant uptake (\( \theta_r \), the residual soil water content) (Table B4).

The saturated soil water contents at the strandveld site are very similar (35.8%, 30.4% and 37.2%) in all three layers (Table B4). The residual soil water contents at the strandveld site are also similar and range from 3.4 to 5.9%. However, there are large differences in the saturated soil water contents at the rooikrans site: 43.6%, 35.4% and 14.7% at the 0.1, 0.5 and 0.9 m depths respectively. The low saturated soil water content at the 0.9 m depth (14.7%) corresponds with the high coarse sand content (13.7) in this layer compared to the other layers (Table B3). The residual soil water contents at the 0.1 and 0.9 m layer (6% and 4.2% respectively) are much higher than that in the 0.5 m layer (0.6%) and correspond with the higher medium sand content and lower clay content compared to the other two layers (Table B3).
Table B3: Soil physical properties at the strandveld and rooikrans sites

<table>
<thead>
<tr>
<th>Site</th>
<th>Depth (m)</th>
<th>Clay</th>
<th>Silt</th>
<th>Fine sand</th>
<th>Medium sand</th>
<th>Coarse Sand</th>
<th>Stone</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strandveld</td>
<td>0.1</td>
<td>1.5</td>
<td>1</td>
<td>29.1</td>
<td>68</td>
<td>0.7</td>
<td>0</td>
</tr>
<tr>
<td>Strandveld</td>
<td>0.5</td>
<td>1.8</td>
<td>1</td>
<td>19.8</td>
<td>73.8</td>
<td>4</td>
<td>0</td>
</tr>
<tr>
<td>Strandveld</td>
<td>0.9</td>
<td>1.3</td>
<td>0</td>
<td>25.8</td>
<td>70.5</td>
<td>2</td>
<td>0</td>
</tr>
<tr>
<td>Rooikrans</td>
<td>0.1</td>
<td>1.2</td>
<td>0</td>
<td>23.6</td>
<td>71.5</td>
<td>3.4</td>
<td>0</td>
</tr>
<tr>
<td>Rooikrans</td>
<td>0.5</td>
<td>0.9</td>
<td>0</td>
<td>19.9</td>
<td>73.4</td>
<td>5.6</td>
<td>0</td>
</tr>
<tr>
<td>Rooikrans</td>
<td>0.9</td>
<td>1.2</td>
<td>0</td>
<td>21.6</td>
<td>63.4</td>
<td>13.7</td>
<td>0</td>
</tr>
</tbody>
</table>

Table B4: Water retention characteristics at the strandveld and rooikrans sites

<table>
<thead>
<tr>
<th>Study sites</th>
<th>Depth (m)</th>
<th>( \theta_r ) ( \text{cm}^3 \text{cm}^{-3} )</th>
<th>( \theta_s ) ( \text{cm}^3 \text{cm}^{-3} )</th>
<th>( \alpha )</th>
<th>( n )</th>
<th>( m )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Strandveld</td>
<td>-0.1</td>
<td>0.0344</td>
<td>0.3578</td>
<td>0.0817</td>
<td>1.6043</td>
<td>0.3767</td>
</tr>
<tr>
<td></td>
<td>-0.5</td>
<td>0.0539</td>
<td>0.3041</td>
<td>0.0221</td>
<td>5.6231</td>
<td>0.8222</td>
</tr>
<tr>
<td></td>
<td>-0.9</td>
<td>0.0586</td>
<td>0.3716</td>
<td>0.0207</td>
<td>7.0946</td>
<td>0.8590</td>
</tr>
<tr>
<td>Rooikrans</td>
<td>-0.1</td>
<td>0.0603</td>
<td>0.4357</td>
<td>0.0263</td>
<td>8.0412</td>
<td>0.8756</td>
</tr>
<tr>
<td></td>
<td>-0.5</td>
<td>0.0062</td>
<td>0.3543</td>
<td>0.0202</td>
<td>10.8288</td>
<td>0.9077</td>
</tr>
<tr>
<td></td>
<td>-0.9</td>
<td>0.0417</td>
<td>0.1465</td>
<td>0.0094</td>
<td>5.0540</td>
<td>0.8021</td>
</tr>
</tbody>
</table>

Figure B9: \( \text{pH (KCl)}^6 \) at the strandveld and rooikrans sites

---

\(^{6}\) The pH of the soil indicates the degree of acidity of the soil to the suspension medium.
B6.2 Water levels

Although we attempted to identify two sites where the water tables were at a similar depth, the data shows that the depths differed significantly (Figures B11 and B12). The depth to the water table at site B has been consistently deeper than that at site A for about the last 20 years. Even the shallowest depth at site, which is the borehole closest to the measuring site (Figure B6), the depth is twice that at the strandveld site.

B6.3 Vegetation structure

The selected transects illustrate the main features of the different vegetation, namely the strandveld and the invading rooikrans (Figures B13-B14 right and left columns respectively, key in Figure B15). The greater height and size of the rooikrans trees and larger proportion of open areas in these invaded stands is evident. The transects in the rooikrans area included the tall restio tufts characteristic of a mixture of strandveld and fynbos. The strandveld stands have a greater variety of shrub species and the restios were more frequent. In August the strandveld stands also have a well developed groundlayer and understory of annuals and seasonally dormant geophytes but this is not shown in these transects.

This seasonal herbaceous component may account for as much as 50% of the total plant canopy cover and fills the gaps between the shrubs.

The average leaf areas (m²) of the dominant shrub species at the strandveld and rooikrans sites are shown in Figure B16 and Table B5. There is a substantial decline in the leaf area index of the shrub component of the strandveld stand from April to August. This is in line with the natural growth patterns in strand veld (Siegfried, 1981). The vegetative growth flush is in the spring and there is some leaf shedding during the summer. The rooikrans show the converse pattern, with a substantial increase from April to August.

---

Figure B10: Electrical conductivity at the strandveld and rooikrans sites

---

7 The electrical conductivity is a measure of the ability of a material to conduct electricity.
Table B5. Leaf area indexes of the dominant shrub species in the Rooikrans and Thicket stands (m²/m²) based on one m² sample plots

<table>
<thead>
<tr>
<th>Date</th>
<th>180401 Rooikrans</th>
<th>190401 Thicket</th>
<th>070801 Rooikrans</th>
<th>080801 Thicket</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stand 1</td>
<td>0.366</td>
<td>0.49</td>
<td>0.944</td>
<td>0.472</td>
</tr>
<tr>
<td>Stand 2</td>
<td>0.683</td>
<td>0.34</td>
<td>1.181</td>
<td>0.167</td>
</tr>
<tr>
<td>Stand 3</td>
<td>0.479</td>
<td>0.407</td>
<td>0.576</td>
<td>0.213</td>
</tr>
<tr>
<td>Stand 4</td>
<td>0.345</td>
<td>0.757</td>
<td>0.769</td>
<td>0.326</td>
</tr>
<tr>
<td>Stand 5</td>
<td>0.645</td>
<td>0.531</td>
<td>0.737</td>
<td>0.41</td>
</tr>
<tr>
<td>Stand 6</td>
<td>1.396</td>
<td>0.842</td>
<td>0.881</td>
<td>0.269</td>
</tr>
<tr>
<td>Stand 7</td>
<td>0.491</td>
<td>0.802</td>
<td>0.734</td>
<td>0.345</td>
</tr>
<tr>
<td>Stand 8</td>
<td>0.474</td>
<td>0.386</td>
<td>1.21</td>
<td>0.177</td>
</tr>
<tr>
<td>Stand 9</td>
<td>0.372</td>
<td>0.47</td>
<td>0.328</td>
<td>0.127</td>
</tr>
<tr>
<td>Stand 10</td>
<td>0.286</td>
<td>0.589</td>
<td>0.564</td>
<td>0.241</td>
</tr>
<tr>
<td>Average</td>
<td><strong>0.554</strong></td>
<td><strong>0.561</strong></td>
<td><strong>0.792</strong></td>
<td><strong>0.275</strong></td>
</tr>
<tr>
<td>St Dev</td>
<td>0.322</td>
<td>0.181</td>
<td>0.274</td>
<td>0.112</td>
</tr>
</tbody>
</table>

Some additional observations were made by the students during their sampling visits. There was a calcrete outcrop in the dune swale area on the east side of the Rooikrans site. This would have little effect on the measured evaporation but there may be further calcrete under the dunes on which the rooikrans grows. The effects of the calcrete are not known but we believe it is unlikely to have significant impact on the plants ability to reach groundwater as roots can penetrate very small cracks (Le Maitre et al., 1999). The dunes were more pronounced on the Rooikrans site and there were large areas of open sand which did not develop any herbaceous cover during the winter. There were frequent patches of indigenous vegetation in the Rooikrans site, some of which were large (Figure B13). This indigenous vegetation appeared to be very vigorous. The Rooikrans trees are taller than indigenous the vegetation.

The Rooikrans appeared to be more affected by the winter rainfall rain. During the initial visits to the site on 5 April 2001 the leaves of the Rooikrans were generally a greenish-yellow to yellow colour and large quantities of leaves had been shed. This seemed to be the result of the dry summer conditions because they grew many new leaves immediately after the first rains. The indigenous vegetation did not appear to be affected by the summer drought and maintained a healthy condition. By the time of the second data collection on 7 August 2001 the Rooikrans had already formed seedpods, suggesting that it makes use of the higher availability of water during winter to complete its reproductive cycle. The indigenous plants had formed buds and were starting to produce new growth and new leaves by the time of the second collection on 8 August 2001. They still had less leaf area per square metre than they had had during the first data collection in April (Figure B16).

B6.4 Evaporation measurement

The components of the energy balance equation, general climatic conditions and the soil water content (Equation B.1) were measured from approximately 1 December 2000 until 1 September 2000. One cloudless day from each season:

- summer – 14 February (rooikrans site) and 16 February (strandveld site),
- autumn – 18 April (rooikrans site) and 30 April (strandveld site), and
- winter – 23 June (rooikrans site) and 13 July (strandveld site)

was selected and will be used in the energy balance comparisons and analysis.
Figure B11: Depths to the water table measured at monitoring boreholes located close to site A, the strandveld site.

Figure B12: Depths to the water table measured at monitoring boreholes located close to site B, the Rooikrans site.
Figure B13: Selected stand structure profiles from the April sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15.
Figure B14: Selected stand structure profiles from the August sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15.
Figure B15: Key to the plant species in the structure profiles

- Acacia cyclops
- Chrysanthemoides monilifera
- Euclia racemosa
- Metalasia muricata
- Olea exasperata
- Restionaceae
- Rhus glauca
- Rhus laevigata var. villosa
- Salvia species

Figure B16: Average leaf area indexes (m²/m²) at the dune thicket (Strandveld) and Rooikrans sites during autumn and winter 2001.
B6.5 General climatic conditions

B6.5.1 Rainfall

The total rainfall recorded during this 10 month period was 414.6 mm (up to 1 September) and exceeded the 21-year long-term average rainfall at Koeberg by 99 mm (31%). Ninety two percent of the rainfall fell from May until the end of August 2001 (Figure B17).

B6.5.2 Reference evaporation

Maximum daily average reference evaporation during December 2000 and January 2001 (6.3 mm day\(^{-1}\)) exceeded the winter reference evaporation values by 4.2 mm day\(^{-1}\) (Figure B17). The lower reference evaporation during winter was due to the decrease in air temperatures (21.3 °C to 12.6 °C) and solar radiation (35.2 MJ m\(^{-2}\) day\(^{-1}\) to 9.37 MJ m\(^{-2}\) day\(^{-1}\)), and increase in rainfall (0 mm month\(^{-1}\) to 191.8 mm month\(^{-1}\)) from summer to winter.

B6.6 Evaporation measurements

The energy balance components (Equation B.1) and therefore, the evaporation, were measured with the Bowen ratio energy balance technique from December 2000 to September 2001 (Table B2). Unfortunately, this proved to be more problematic than we initially realised, partly because of difficulties with some of the sensors and the solenoids which switch measurements from the lower to the upper arm and vice-versa. The main difficulty arose because the technique depends on the differences in the air temperature and vapour pressure deficit (air dryness) profiles being greater than the instrument measurement resolution and accuracy. These gradients often were not greater than the measurement errors, probably because the relatively windy conditions and the roughness of the plant canopies resulted in a substantial amount of turbulence and mixing of the air.

B6.6.1 A comparison of the profile differences above strandveld and rooikrans canopies

B6.6.1.1 Vapour pressure measurements

Mean diurnal courses of water vapour pressure differences (over a distance of 1.50 m) above the strandveld and rooikrans vegetation, are given in Figure B18. Under the conditions prevailing at the study sites, the water vapour pressure differences were not only small, but the dewpoint temperatures were very close to air temperature, indicating that the air was nearly saturated with water. Another cause of the small water vapour pressure differences is the dew-10 (dewpoint and water vapour pressure) sensor's inability to stabilize at dewpoint, which results in unrealistic or even negative dewpoints and low water vapour pressures and water vapour pressure differences.

During summer and winter, the measured water vapour pressure data at both the rooikrans and strandveld sites were unreliable (Figure B18). During summer, the solenoid was not functioning at the rooikrans site, and the dew-10 sensor was not functioning properly at the strandveld site, resulting in negative dewpoints at the strandveld site. During winter, the dew-10 sensor was not functioning properly at both the strandveld and rooikrans site, hence the low water vapour pressure differences. We would, therefore, have expected to measure greater water vapour pressure differences at both the strandveld and rooikrans sites had all the sensors been functioning properly.

During autumn, only the water vapour pressure differences measured between 10h00 and 13h00 in the day exceeded the resolution limits of the dew-10 sensor (Figure B19). However, the measured values were negative suggesting that there were vapour pressure inversions, but it is not clear why.
Figure B17: Summary of the monthly total rainfall (rain), monthly average reference evaporation ($E_{To}$), monthly total solar radiation ($R_s$), and the monthly mean air temperature ($T_a$) measured from 30 November 2001 to 1 September 2001.
Figure B18: Water vapour pressure difference at the strandveld and rooikrans sites during three selected days representing summer, autumn and winter conditions.

Figure B19: Water vapour pressure difference at the strandveld and rooikrans sites during autumn
B6.6.1.2 Energy available for evaporation

Evaporation also can be estimated directly from measurements of the energy available to drive evaporation (i.e. the latent heat flux density, LHFD or $\lambda E$) above the vegetation canopy. The LHFD is calculated from the vapour pressure gradient, net radiation, soil heat flux density and other climate parameters. The measured Bowen Ratio (bet) and potential (eqet) $\lambda E$ above a strandveld and rooikrans canopy are shown in Figure B19. Most of the $\lambda E$ data were rejected as a result of sensor problems. During summer and winter, the rooikrans $\lambda E$ values are slightly lower than those for strandveld, and the potential rooikrans $\lambda E$ values are slightly smaller than those for strandveld. However, during autumn, the measured Bowen Ratio (bet) and potential (eqet) $\lambda E$ values at the rooikrans site exceeded those at the strandveld site. The total daily potential $\lambda E$ (eqet) at the strandveld site (14.6, 7.0 and 3.9 MJ m$^{-2}$ day$^{-1}$ during summer, autumn and winter respectively) differed slightly from that at the rooikrans site, being 13.6, 8.2 and 3.7 MJ m$^{-2}$ day$^{-1}$ during summer, autumn and winter respectively. These differences are directly related to the small potential evaporation differences (strandveld minus rooikrans) of 0.3, -0.4 and 0.2 mm day$^{-1}$ respectively. Therefore, the measured Bowen Ratio $\lambda E$ values (bet) in Figure B20 suggest that the strandveld evaporation could exceed that at the rooikrans site during summer and winter, and the rooikrans evaporation that at the strandveld site during autumn, if the $\lambda Es$ continue the trend seen in Figure B20.

As a result of sensor problems, the comparison of the water vapour pressure differences and latent heat flux densities does not clearly show that there were differences in evaporation between the two sites. An analysis of the available energy (net radiation and soil heat flux density) as well as the air temperature profile differences, and the soil water contents monitored at both site, might show that there were differences in energy partitioning and, thus, in evaporation.

Figure B20: Latent heat flux densities at the strandveld and rooikrans sites for three selected days representing summer, autumn and winter conditions.

Note: bet refers to the latent heat flux density as calculated from the Bowen ratio energy balance data, in other words real evaporation, whereas eqet refers to the latent heat flux density for potential evaporation (equilibrium equation), in other words, the potential latent heat flux density.
B6.6.2 A comparison of temperature profile differences at the two sites during different seasons

The air temperature profile differences were compared only for periods when the air temperature profile differences were positive at the two research sites, i.e. when the data showed that the upper air temperature was cooler than the lower air temperature. During summer and autumn the differences between the strandveld and rooikrans site averaged 75%, with the strandveld air temperature differences exceeding those at the rooikrans site (Figure B21). The vertical distance over which these air temperature differences were measured, was 1.50 m. During winter, though, the conditions were reversed with the air temperature profile differences at the rooikrans site exceeding those at the strandveld site by 77%.

![Air temperature profile differences at the strandveld and rooikrans sites for three sample days during summer, autumn and winter](image)

The smaller air temperature profile differences at the rooikrans site could, in part, have been due to the fact that the instrumentation was installed on a much higher tower than at the strandveld site. The instrumentation was therefore in a portion of the overall air temperature profile where the gradients are much steeper when compared with the height of the measurements at the strandveld site. The effects of this on the measured seasonal differences described above are not clear.

B6.6.3 How does this affect evaporation?

B6.6.3.1 A comparison of the energy balances at the strandveld and the rooikrans sites

The water vapour pressure profile differences at both the strandveld and rooikrans sites were very small, generally falling within the resolution limits of the dew-10 vapour pressure sensor. Therefore, most of the data vapour pressure data were rejected from usage in the calculation of evaporation at the different research sites. However, the net radiation and soil water content data collected revealed a lot about the characteristics of the different plant communities. The net radiation ($R_n$), soil heat flux density ($G$), available energy ($R_n-G$) and soil water content at both the strandveld and rooikrans sites were therefore compared to aid our understanding of the possible differences in water use (evaporation).
The data were divided into three seasons, summer (16 and 14 February), autumn (30 and 18 April) and winter (13 July and 23 June) with the dates in brackets referring to a strandveld and rooikrans day measurement days respectively. One cloudless day was used for comparison during each season.

B6.6.3.2 A comparison of the available energy, net radiation and soil heat flux density at the two sites during different seasons

The available energy (Rn-G) can be partitioned between the energy driving evaporation (i.e.) and that heating the air (H). The more the energy available, the more the potential evaporation.

During summer and winter, the available energy at the strandveld site exceeded that at the rooikrans site by 1.5 (7%) and 0.7 MJ m$^{-2}$ day$^{-1}$ (11.7%) respectively (Figure B22). However, during autumn, the available energy at the rooikrans site exceeded that at the strandveld site by 1.1 MJ m$^{-2}$ day$^{-1}$ (9.8%). That means that during summer and winter, there was more energy available to be partitioned between the latent and sensible heat flux densities at the strandveld site, compared to the rooikrans site (Figure B22). These measured differences in the available energy are best explained and understood by comparing the differences in the net radiation (net incoming and outgoing solar radiation consisting of long and short waves) and the soil heat flux density (energy heating the soil) caused by the canopies of the different vegetation types.

During summer and autumn, the soil heat flux densities generally reduce the net radiation only by a small percentage: 1 to 5% of the daily total. However, during winter, this percentage ranges between 10 and 15% for daytime values, and could be even higher (using the MJ m$^{-2}$ day$^{-1}$ values). One could therefore say that the available energy is mainly governed by the net radiation, and that the soil heat flux densities contribute only a small percentage.

Figure B22: Available energy at the strandveld and rooikrans sites, and the difference in the available energy between these sites for three sample days during summer, autumn and winter
B6.6.4 Effective degree of saturation and profile soil water storage at the strandveld and rooikrans sites

A comparison of the net radiation at the strandveld and rooikrans sites shows the same trends as the available energy. The net radiation at the strandveld site exceeds that at the rooikrans site during both summer and winter, but not during autumn (Figure B23). During summer, large differences occur between the soil heat flux densities at the two sites (Figure B24). The strandveld soil heat flux density exceeds that at the rooikrans site by 75%. No soil heat flux density differences were measured during autumn, but during winter, the soil heat flux density at the rooikrans site, exceeded that at the strandveld site by 25%. The higher soil heat flux density during summer at the strandveld site suggests that it had a lower leaf area index than the rooikrans site. The lower soil heat flux density at the strandveld site during winter suggests that it had a higher leaf area index than the rooikrans site. These differences can be explained by the plant stress and seasonal leaf growth and losses by the dominant plant species. The lower G values at the strandveld site during winter, compared with the rooikrans site, suggest that the rooikrans lost a lot of leaves due to severe moisture stress, probably in the autumn. The lower soil heat flux density during summer at the rooikrans site suggests that the rooikrans had high leaf areas and were still growing strongly at that time.

In summary, the energy available to drive evaporation at the strandveld site exceeds that at the rooikrans site during summer and winter, with their relative positions being reversed in during autumn.

The effective degree of saturation of the soil layers at the strandveld and rooikrans sites are compared in Figure B25. The upper soil layer (0.05 m) at both the strandveld and rooikrans site was drier than the 0.50 m layer throughout the year. The degree of saturation in the upper soil layer is less than the deeper layer, because it is exposed to wind and solar energy. Continual drying of the upper soil layer, for example during summer when there is no rainfall, can lead to extremely low degrees of saturation (less than 5%). The effective degree of saturation of the deeper soil layer (0.50 m) at the strandveld site, increased from summer to autumn, and significantly from autumn to winter, following the first rains (Figure B25). The effective degree of saturation of the 0.50 m soil layer at the strandveld site exceeded that at the rooikrans site by 35% (summer) to 40% (winter).

The soil profile, up to 1.00 m below the soil surface, contains less water at the rooikrans site than at the strandveld site throughout the year. This is despite the potential profile soil water at the rooikrans site exceeding that at the strandveld site by approximately 50 mm. The soil water content differences between the strandveld and rooikrans sites (over a 1.0 m profile) were approximately 80 mm during summer, 90 mm during autumn and 120 mm during winter (Figure B26). During summer, both strandveld and rooikrans utilize the soil water, but the rooikrans utilizes the soil water more than the strandveld and therefore has a lower profile soil water content. During autumn, the profile water content differences between the two sites increase even further, with the profile water content increasing at the strandveld site and that at the rooikrans site decreasing.

However, a comparison of the extent to which the soil profiles have been filled (Figure B27), shows clearly that the strandveld profile held more water (a greater percentage of its total capacity) during the whole year than the rooikrans site. During summer, the strandveld site had 27% more available water than the rooikrans site, during autumn, 33% and during winter 40%. These differences suggest:

- That more water was available for total evaporation at the strandveld site than at the rooikrans site. This might explain why the strandveld could have higher evaporation rates during winter and summer than the rooikrans.
- Alternatively, the higher moisture contents at the strandveld site suggest that the measured evaporation at the rooikrans is underestimated and this is why the soil moisture levels are lower despite getting essentially the same rainfall inputs. This alternative is partially supported by the
observations of the severe moisture stress in the rooikrans in the late summer and early autumn and its rapid recovery after the first rains.

- A third alternative is that the indigenous shrubs are using water from the capillary fringe above the groundwater rather than the vadose (unsaturated) zone but the rooikrans can only use water from the vadose zone. This is highly likely given the much greater depths to the water table at the Rooikrans site (Figure B11 vs Figure B12).

The lower moisture levels in the soil profile at the rooikrans site imply that it could store and retain more of the rainfall and, therefore, that the recharge to the groundwater (several metres below the surface) would be lower than under the strandveld.

![Graph showing net radiation and soil heat flux density](image)

**Figure B23:** Net radiation at the strandveld and rooikrans sites, and the difference in the net radiation between these sites for three sample days during summer, autumn and winter

![Graph showing soil heat flux density](image)

**Figure B24:** Soil heat flux density at the strandveld and rooikrans sites, and the difference in the soil heat flux density between these sites for three sample days during summer, autumn and winter
Figure B25: Effective degree of saturation at the strandveld and rooikrans sites at 80 mm and 500 mm below the soil surface for three sample days during summer, autumn and winter.

Figure B26: Profile soil water content at the strandveld and rooikrans sites over a depth of 1000 mm for three sample days during summer, autumn and winter.
B6.6.5 Summary

The Bowen Ratio energy balance system collects information regarding the energy partitioning above a plant canopy. The accuracy of the measurements of the different components determines the accuracy and validity of the evaporation estimates. Above certain canopy types, especially rough surfaces like forests and some natural vegetation types, the water vapour pressure differences are inherently very small.

During this study the differences in the measured water vapour pressure deficits at two heights (1.50 m apart) were often less than 0.01 kPa, beyond the limits of resolution of the dew-10 sensor which is the most accurate one available at present. Some of the small differences were due to equipment failure, but most of them probably were due to mixing of the air (turbulent flow) above the relatively rough vegetation canopy. The very small measured differences had to be rejected as they could not be used to calculate evaporation. In the end we could not even estimate the evaporation for a single day. However, we can still draw some conclusions from an analysis of the data on the available energy flux density, the air temperature profile differences and the available soil water (Table B6).

A comparison of the few evaporation data points in Figure B28 shows clearly that during summer and winter the strandveld evaporation exceeds that at the rooikrans site. There was more soil water available at the strandveld site and this may account for the evaporation at the strandveld site exceeding that at the rooikrans site (Figures B25-B27). However, during autumn, even though more soil water was available at the strandveld site, there was more energy available for evaporation at the rooikrans site than at the strandveld site. This is clear from Figure B28, where the Bowen ratio and equilibrium evaporation at the rooikrans site, exceeded that at the strandveld site. The relatively dry soils recorded at the rooikrans site also may have been due to cumulative soil moisture depletion during the dry summer and autumn periods from 1997-2000 (Figure B3).
Table B6: Summary of available energy and air temperature profile difference at the strandveld and rooikrans site during the three seasons studied

<table>
<thead>
<tr>
<th>Component</th>
<th>Summer</th>
<th>Autumn</th>
<th>Winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>( R_n - G )</td>
<td>Strand &gt; Rooi (7%)</td>
<td>Strand &lt; Rooi (10%)</td>
<td>Strand &gt; Rooi (11%)</td>
</tr>
<tr>
<td>( dT )</td>
<td>Strand &gt; Rooi (75%)</td>
<td>Strand &gt; Rooi (75%)</td>
<td>Strand &lt; Rooi (77%)</td>
</tr>
<tr>
<td>Comment</td>
<td>More available energy at the strandveld site</td>
<td>More available energy at the rooikrans site</td>
<td>More available energy at the strandveld site</td>
</tr>
</tbody>
</table>

dT small at rooikrans, therefore most of energy possibly to Latent heat flux density at Rooikrans
Evaporation possibly higher at rooikrans than strandveld

The equilibrium (potential) evaporation indicates that the potential evaporation at the strandveld and rooikrans sites is very similar. The potential evaporation at the strandveld (4.9 mm day\(^{-1}\) and 3.9 mm day\(^{-1}\) for summer and winter respectively) site exceeded that at the rooikrans site (4.6 mm day\(^{-1}\) and 3.7 mm day\(^{-1}\) for summer and winter respectively) during summer and winter. However, during autumn, the potential evaporation for the rooikrans (2.7 mm day\(^{-1}\)) exceeded that at the strandveld site (2.3 mm day\(^{-1}\)).

Figure B28: Bowen ratio evaporation (bet) and equilibrium evaporation (eqet) at the strandveld and rooikrans sites for three sample days during summer, autumn and winter.
**B6.7 Remote sensing analysis**

The classification of the high-resolution image appeared to be successful but it was not. The MrSid images are made up by joining together aerial photographs which have been colour balanced to a certain extent. Unfortunately, in this case the colour depth and degree of contrasts in the different aerial photographs happened to coincide, at least within the study area, with the boundaries between the invaded and uninvaded vegetation. This created the false impression of a successful classification. We could not correct this problem with the time and resources available to us but it does emphasise the importance of doing a proper assessment of any classification of a remote sensed image before drawing any conclusions.

Further remote sensing analyses are planned (see Methods section)

**B7. CONCLUSIONS**

**B7.1 Vegetation**

This analysis has supported other work which has shown that invasions by rooikrans change the structure of the vegetation and increase the biomass (Versfeld and Van Wilgen, 1986, Richardson et al., 1992). The leaf area index data and the field observations both show that the leaf areas of the rooikrans increased markedly from April to August while those of the strandveld shrubs decreased. This may have been compensated for by the development of a vigorous herbaceous layer in the strandveld which was not quantified in this study.

The high moisture stress levels in the rooikrans during autumn indicate that it may not be using groundwater directly or that the groundwater level at that time was too far below the surface for its root systems to reach. No root studies were done on this site but a number of the indigenous shrub species (Olea, Rhus, Euclea) are known to be deep rooted and could be using groundwater.

**B7.2 Water levels**

The water levels at the rooikrans site were much deeper than those at the strandveld site (Figure B11 vs B12), so it is very likely that the rooikrans is not able to make use of the groundwater. This could explain why the rooikrans showed much greater drought stress than the strandveld during the late-summer and autumn.

**B7.3 Evaporation**

The measurement of evaporation using the Bowen Ratio has not been successful so far. This is partly due to instrument failure but in most cases probably was due to the relatively rough canopies and the turbulence of the air flowing over the vegetation. This resulted in vapour pressure gradients that were too small to detect reliably using this apparatus. The limited evaporation data that could be used appear to indicate that evaporation from strandveld is higher in summer and winter and vice versa in autumn. On the other hand the soil moisture data indicate that the strandveld soils remain moister than those at the rooikrans site. Since they receive the same rainfall, this suggests that:

- either the rooikrans soils must be better drained;
- or that the rooikrans is using more water than the strandveld on an annual basis (and thus cumulatively over the dry years from, 1997 to 2000);
- or that the strandveld shrubs are behaving like phreatophytes and using groundwater while the rooikrans is not using or able to access the groundwater.
In other words the indigenous shrubs are using water from the capillary fringe above the groundwater rather than the vadose (unsaturated) zone but the rooikrans can only use water from the vadose zone. The drier soil profile at the rooikrans site also implies that it may retain more of the rainfall and thus reduce the net recharge to the aquifer relative to strandveld.

B7.4 Tracer studies

It is hoped to conduct tracer tests on groundwater use during the dry season. The uncharacteristic summer rainfall during 2001/2002 increased soil moisture and meant that this was not feasible as part of this study.

B7.5 Remote sensing analysis

Classification of the high resolution image of the study area (Figure B4) was not successful. Further work using remote sensing has been planned.

B8. Acknowledgements

We thank the Water Research Commission for funding this study. We thank Eskom, particularly Mr G Greef (Environmental Manager, Koeberg), for supporting this study by giving us free access to the area, providing data and ensuring that the Rooikrans study site was kept free of woodcutters for the duration of this study. We also thank the CSIR for supporting the complementary study on the water-use by the vegetation and supplying and maintaining the Bowen Ratio measuring equipment. The field sampling was conducted by Carin Jarmain and Godfrey Moses of the CSIR and Iptieshaan Kippie and Morné Magerman of UWC. Their work is gratefully acknowledged.
ADDENDUM 1.
A LIST OF THE DOMINANT SPECIES RECORDED DURING THE VEGETATION SURVEY.

Acacia cyclops
Chrysanthemoides monilifera
Metalasia muricata
Putterickia pyracantha
Rhus laevigata var. villosa
Rhus glauca
Zygophyllum flexuosum
Asparagus compactus
Asparagus rubicundus
Thamnochortus spcigerus
Staberoha distachyos
Chondropetalum tectorum
Olea exasperata
Euclea racemosa
Tetragonia fruticosa
Salvia lanceolata
Salvia africana-coerulea
Ruschia mocawani
Carpobrotus edulis
REFERENCES


Clifton, C. and Evans, R. undated. A framework to assess the environmental water requirements of groundwater dependent ecosystems. Unpublished manuscript.


CRCCH 1996. Field measurements techniques in hydrology. Workshop Notes. Cooperative Research Centre for Catchment Hydrology, Monash University, Australia.


Davis, SD 1995. Ecophysiological processes and demographic patterns in the structuring of Californian chaparral. MS for Chile Medecos Volume.


De Beers, n.d. (no date). The Venetia balance – diamonds, water and environmental responsibility. De Beers Consolidated Mines, Corporate Communications Department (Kimberly?).


Greenspan nd. Sapflow measurement with the Greenspan sapflow sensor: theory and technique. Greenspan Technology, Warwick, Queensland, Australia.


Actual evaporation

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

Aerial Photography

In general, aerial imagery is used to focus on specific areas of interest, often identified using other mapping techniques, including coarser scale RS images. Conventional aerial photography is still an extremely useful resource for mapping ecosystems. Its spatial resolution is entirely dependant upon flight altitude and infrared and thermal film can be loaded into the cameras to produce alternate images of the earth. Often considered an expensive option, due mainly to climatic constraints and the expenses incurred by tasking a specific flight rather than buying data from an already orbiting platform, aerial photography is still considerably cheaper than modern very high resolution sensors such as IKONOS. If aerial photography is ortho-rectified it can be an extremely accurate and effective tool, for many different kinds of mapping. One advantage of aerial photography is that it is often high resolution and therefore very useful for determining species type. This is performed primarily by using field knowledge and aerial photography interpretation skills, as the photographs do not yield the same level of spectral information that a multi-spectral digital sensor would. This kind of photo-interpretation of course requires specialist training and experience. If the photographs are required to be used within a GIS environment, then ortho-correction and mosaicing the photographs can be time consuming and also requires specialist skills and training. Digital/Hyper-spectral - Some digital and hyper-spectral sensors are available in Southern Africa however these options are more expensive than standard airborne sensors. These products usually yield considerably more information than standard aerial photography, even to the level of plant species/type determination.

Some examples of airborne digital scanners are:

Daedalus – Airborne Thematic Mapper
AVIRIS Hyper-spectral scanner
ARC Airborne multi-spectral video imager
AATS Thermal Scanner
HyVista Hyper-spectral Scanner

These products offer high ground resolution plus finely tuned and optimised spectral bands. These options should be utilised when focussing upon a small area. The nature of the hyper-spectral sensors is such that if field data (accurate spectrometry measurements) are collected for particular species and radiometric corrections are performed, then species level mapping is possible.
<table>
<thead>
<tr>
<th>Term</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Alluvial aquifer</td>
<td>An aquifer formed of unconsolidated sediments deposited by a river or stream; typically occurring beneath or alongside a current channel, or in an buried old or paleo-channel of the river.</td>
</tr>
<tr>
<td>Annual plant</td>
<td>A plant which completes its life cycle within one year or one growing season; i.e. it grows vegetatively, produces flowers and sets seed in one season.</td>
</tr>
<tr>
<td>Aquatic ecosystem</td>
<td>Not defined in the National Water Act. They are defined in the water quality guidelines (DWAF, 1996) as the abiotic (physical and chemical) and biotic components, habitats and ecological processes contained within rivers and their riparian zones, reservoirs lakes and wetlands and their fringing vegetation. Terrestrial biota, other than humans dependent on aquatic systems for their survival are included in this definition.</td>
</tr>
<tr>
<td>Aquifer</td>
<td>A geological formation which has structures or textures that hold water or permit appreciable water movement through them (Water Act, 1998).</td>
</tr>
<tr>
<td>Biodiversity</td>
<td>Biodiversity is 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).</td>
</tr>
<tr>
<td>Biome</td>
<td>A broad ecological unit representing major life zones of large areas. In South Africa these are defined mainly by vegetation structure and climate (Low and Rebelo, 1996).</td>
</tr>
<tr>
<td>Capillary fringe</td>
<td>The lower division of the zone of aeration (vadose zone) that overlies the zone of saturation and in which the pressure of water in the interstices is less than atmospheric (McGraw-Hill, 1978).</td>
</tr>
<tr>
<td>Coastal forest</td>
<td>Medium to tall forest vegetation dominated by evergreen trees, climbers and shrubs, often associated with coastal lakes and swamps. Distributed from Alexandria to the Mozambique border. 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).</td>
</tr>
<tr>
<td>Ecosystem</td>
<td>An interconnected and interacting system comprising living organisms - including animals, plants, fungi, and microorganisms - and their non-living environment.</td>
</tr>
</tbody>
</table>
Emboli

An embolism forms when the vessels in the xylem (water transporting tissues) of a plant form gas bubbles because of the high tensions induced by water shortage. Emboli block the vessels and stop water transport through them. When a large proportion of these vessels are blocked by emboli the plant cannot supply enough water to its leaves to prevent wilting and death.

Ephemeral

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

Evaporation

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

Evapotranspiration

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

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).

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).

Geological formation

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

Groundwater body

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

See plant growth form.

**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.

**IKONOS1**

IKONOS1 is the first commercially available ultra-high spatial resolution data satellite. Operated by the American company Space Imaging, the imagery is produced as a range of products, varying in price depending upon accuracy required and ground control used to geometrically correct the imagery. IKONOS data has recently become available in Southern Africa and is currently distributed through Space Imaging Africa, based in Johannesburg. Another advantage of IKONOS, apart from the extremely high ground resolution, is that the sensor can be pointed off nadir to collect data away from its path, hence increasing data collection speed. The Carterra products offered by Space Imaging vary in spatial accuracy with an RMSE of between 12m and 1m depending upon the ground control provided. The higher accuracy products are subsequently more expensive as they require more ground control points and processing. In a South African context, this kind of data will be considered very expensive. It could almost be said unsustainable. For the minimum area of 5 x 5 km the lowest accuracy level data is R12 775. Pricing issues aside, IKONOS could be implemented at a very high level and used for small scale monitoring, looking at key areas within an ecosystem.

**Interception**

Water from precipitation which is retained on the surfaces on which it lands (for example leaves, bark, vegetation, litter) and lost by evaporation.

**Keystone ecosystem**

An ecosystem which has a key role in maintaining the function and integrity of the ecosystems which are linked to it, both directly (e.g. riparian vegetation as a link between the terrestrial and aquatic ecosystems) or indirectly (e.g. discharge from a wetland which maintains downstream ecosystems). It is the ecosystem-level analogue of a keystone species.

**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).

**Landsat**

Landsat 1 was launched in, 1972 and became the first satellite to produce commercially available Earth Observation (EO) imagery. The series is still running today with the launch and successful operation of Landsat 7 in, 1999. Landsats 1 – 5 all featured the Multi-spectral Scanner (MSS) instrument. This sensor was the mainstay of the programme until, 1982 when the Thematic Mapper (TM) was included on Landsat 4. This took over the main Earth Observation role from MSS.
as it offered higher spatial and spectral resolution data, thus opening up the applications base. Landsat 7's new Enhanced Thematic Mapper (ETM+) sensor now takes the programme into the next level of EO. With very similar capabilities to TM the ETM+ also includes a higher resolution 15m panchromatic band. This again increases and improves Landsat's role in a number of new and existing applications.

The ETM+ sensor was originally planned for Landsat 6, but the platform suffered onboard failures shortly after attaining orbit in, 1993. Landsat MSS - MSS is a relatively low resolution multpectral sensor that is good for mapping vegetation and vegetation change on a broader scale.

The Satellite Applications Centre (SAC) has a Landsat MSS archive that runs from, 1986 up to, 1993. Landsat TM (Landsats 4 &5) - The higher spatial and spectral resolution of the TM sensor allows much more detailed mapping of ecosystems. Improvements also include better textural differentiation and a better understanding of geological setting. Widely used for a number of environmental applications throughout the world. Large scene size also proves very cost effective. This data is available from SAC, whose archives stretch back to June, 1989. Landsat 7 ETM+ - The new ETM+ sensor has the same spectral characteristics as the TM sensor, but with the added bonus of better spatial resolution in the 15m panchromatic. This will allow more detailed mapping in pan mode or ‘pan-sharpening’ of the multi-spectral data. The scene size is the same as the rest of the Landsat programme and is currently available through the EROS data centre in the United States at $600 per scene. This makes the data the most cost effective alternative for EO applications at this level of detail. ETM+ is still in its infancy, but promises to be very widely utilised, in South Africa as well as internationally as it continues the commonly used TM sensor now a featuring higher spatial resolution panchromatic band.

**Landscape**

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

**Leaf area index**

This 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). The leaf area is measured as the area of the one (upper) side only unless explicitly indicated otherwise.

**Lithostratigraphy**

The science of classifying or organising rock strata according to the properties of the constituent material (Bates and Jackson, 1980).
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 supply or grow where groundwater tables are within reach of their roots and they typically have high transpiration rates. Obligate phreatophytes are completely dependant 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.

Phreatic surface

The upper limit of the saturated zone i.e. the watertable.

Plant growth form

This is a way of grouping or classifying plants based their form or habit, the shape of the parts (morphology) or functional aspects such as their life cycle or leaf longevity (e.g. evergreen versus deciduous). The term “life form” was used to define classes based on the ways in which the plants survive drought conditions.

Plant structure

The form or type, size, shape and arrangements of the plant parts such as leaves, branches or stems. This would include such features as the height of the plant, size and denseness of the canopy and leaf area or leaf area index.

Riparian

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

Regolith

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

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).

SPOT

The European Space Agency (ESA) launched SPOT1, the first SPOT satellite, in 1986. This saw the start of one the first purely commercial satellite programmes. The French Space Agency (CNES) followed this with SPOT2 in, 1990 and SPOT3 in, 1996. SPOT3 failed after launch and SPOT1 was subsequently reactivated. The latest, SPOT4 has improved spectral resolution, with an extra spectral band, plus a new instrument, SPOT Vegetation. SPOT 4 HRVIR often works out to be the more expensive alternative, second only to the new IKONOS sensor. Although the imagery is around the same sort of price as Landsat TM data purchased in South Africa, it is a lot smaller in scene size, approximately 1/9th of a Landsat scene.
Advantages of SPOT data are that its sensors can be pointed off-nadir, thus reducing repeat-period and increasing data availability, plus its spatial resolution in both MS and pan modes is finer than Landsat MSS, TM or ETM+. SPOT HRVIR (High Resolution Visible and Infrared) - Deployed onboard SPOT 2/4, this sensor images the earth in both multi-spectral mode at 20m and panchromatic mode at 10m. SPOT5 will feature the same sensor with increased spatial resolution of 10m multi-spectral and 2.5m panchromatic data.

This is a very good sensor for the detection of vegetation as spectral bands, particularly in the case of SPOT4, are focused around optimal areas of the EMS for maximum plant data collection. SPOT Vegetation - A sensor specifically designed for detecting and measuring vegetation occurrence and production the SPOT 4 Vegetation sensor is ideal for monitoring crops, forests, pastures and rangelands. The data is directly compatible with regular SPOT multi-spectral imagery as the spectral bands have been matched and as they are mounted on the same platform all other parameters are identical.

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.

Thicket

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

Transpiration