ASSESSING TERRESTRIAL GROUNDWATER DEPENDENT ECOSYSTEMS IN SOUTH AFRICA

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Executive Summary

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 a 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.

Objectives of the Project

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 occurence and groundwater requirements of TGDEs.
- Test a selection of these tools at field sites.

Recommendations

Recommendations for further work and coordination of the evolving knowledge base on TDGEs 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 TDGEs 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

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Abbreviations

CMAs	Catchment Management Agencies
DWAF	Department of Waters Affairs & Forestry
KNP	Kruger National Park
NBI	National Botanical Institute
NDVI	Normalised Difference Vegetation Index
NWA	National Water Act of South Africa (1998)
MGSD	Moisture Growing Season Duration
RDM	Resource Directed Measures
RQO	Resource Quality Objective
SASS	South African Scoring System
SASS5	South Africa Scoring System version 5
TGDEs	Terrestrial Groundwater Dependent Ecosystems
TMG	Table Mountain Group
WCNCB	Western Cape Nature Conservation Board
WMA	Water Management Area
WUA	Water User Association

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.

Resource Directed Measures protect the ecological role of groundwater.

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.

1.2 WHAT IS MEANT BY GROUNDWATER DEPENDENCE?

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.

We need to understand the nature, degree and extent of dependency.

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).

CRITICAL DRY-SEASON AVAILABILITY

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 make 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., 19*89). Once the switch has occurred a high degree of intervention may be needed to return the system to its previous state.

NUTRIENTS AND SALINITY CONTROLS OF GROUNDWATER QUALITY

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.

Use vs. Dependency

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.

1.3 WHAT TYPES OF GROUNDWATER DEPENDENCE ARE THERE?

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:

1.3.1 Ecosystems with direct dependency on groundwater

- **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.

1.3.2 Species with indirect dependence

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., 19*98). 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., 19*98).

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.

1.3.3 Dependence and the life-cycle

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., 19*92, 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.

1.4 HOW SENSITIVE ARE PLANTS TO CHANGES IN THE WATER TABLE DEPTH OR SPRING DISCHARGE?

An extensive survey of the available literature and anecdotal information failed to find much information on groundwater dependence of indigenous vegetation in South Africa l*et al*one documented cases of sensitivity to manipulation of the water table (Scott and Le Maitre, 1998, Le Maitre *et al., 19*99). 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., 19*98; Le Maitre *et al., 19*99) (Figure 1). Essentially, plants can utilise groundwater wherever their roots can access it and this may occur at substantial depths. Many tree and shrubs 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., 19*96); 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 basedflow. 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.

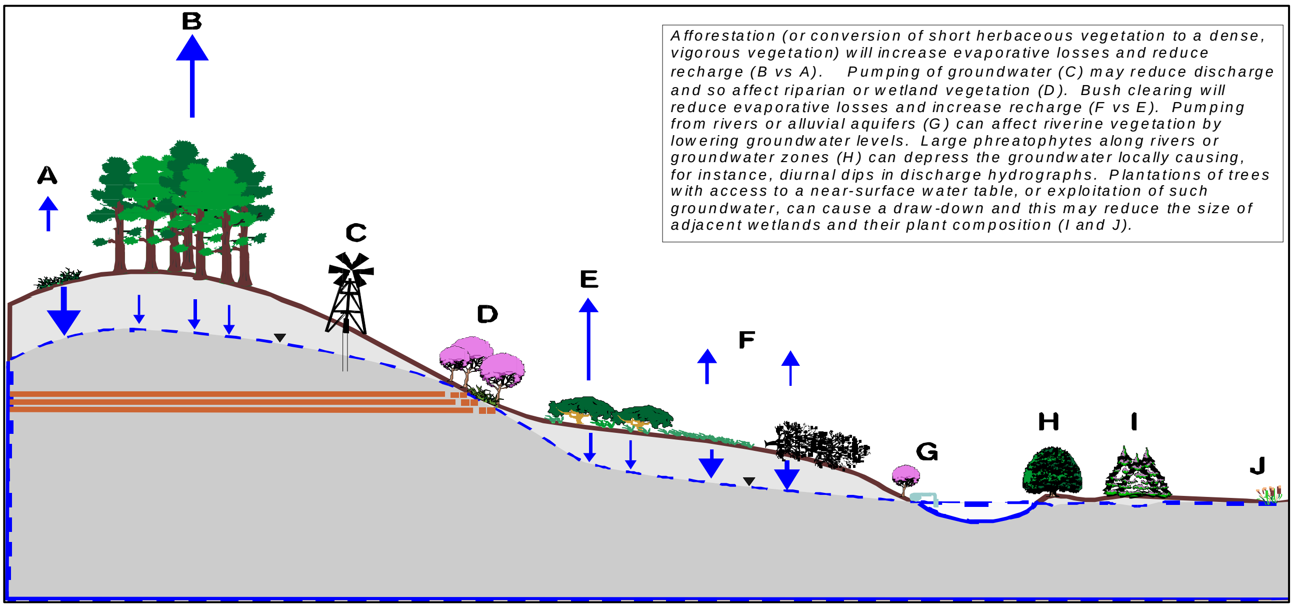


Figure 1: Schematic diagram illustrating some typical interactions between vegetation and groundwater (Scott & Le Maitre, 1998; Le Maitre et al., 1999).

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.

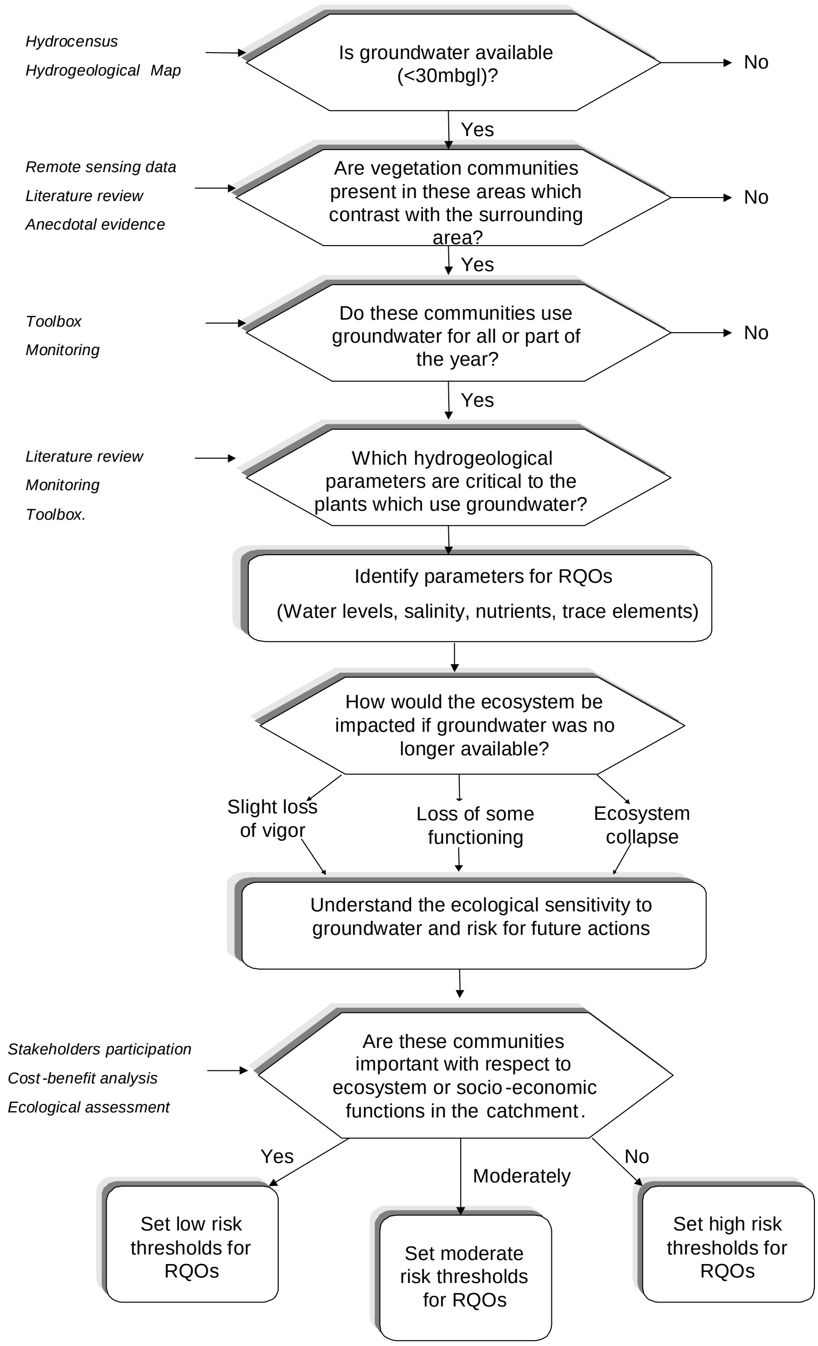


Figure 2: Preliminary protocol to identify groundwater dependent vegetation and set RQOs.

1.7 INDICATORS OF GROUNDWATER USE

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 safe guard 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., 19*99). 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).

COMMUNITY ASSOCIATION WITH TREES/WOODY PLANTS

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., 19*98, 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 river flow 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.

ENVIRONMENTAL TRACERS

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.

Water relations and moisture stress

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., 19*88; 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).

Measuring moisture stress

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).

Estimation and measurement of water-use

Evaporation, including transpiration (water-use) by plants, is inherently difficult to measure (Kelliher *et al., 19*93). 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.

Climatic indexes

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 Schulze (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., 19*95) 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.

Plant community evaporation

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.

Two other techniques which are potentially promising are based on either direct measurements of the temperature of leaves in the plant canopy or the vapour content of the air and the air movements. These are both in the testing stage but they could be suitable very promising for measuring transpiration from small ecosystems where there may be groundwater dependence.

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.

Rooting depth

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

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 (Carlquist, 1977, Tyree and Sperry, 1989, Tyree & Ewers, 1991, Jarbeau *et al., 19*95). 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., 19*87, Pate *et al., 19*95). Wood anatomy can therefore be used to indicate whether a species is deep rooted and likely to be using groundwater.

Xylem structure

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., 19*95). 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., 19*98). 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.

Plant phenology

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 to 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.

Plant leaf area and leaf-area index (LAI)

The volume of water transpired by plants is directly related to the **leaf area** of the plant (Wullschleger *et al., 19*98 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.

Terrill 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 Ind**ex) 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., 19*98).

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.

1.7.3 Remote sensing techniques

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., 19*89).

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.

Mapping Scales

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)

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

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

Sensor / data	*Ground resolution (metres)*	*Maximum cartographic operating scale)*
SPOT Pan	10	1:30 000
SPOT XS	20	1:60 000
LANDSAT TM	30	1:90 000
LANDSAT MSS	80	1:240 000
IKONOS 1	4	1:50 000 – 1:2 500

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

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

** 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 180km) 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 2250km) in 4 spectral bands, finely tuned to detect vegetation patterns and changes. Both of these satellites have coarse spatial resolution of 1km 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 (185kmx185km) and considerably cheaper. It is slightly coarser in spatial resolution (30m pixels rather than SPOTs 20m in multi-spectral mode) but has a greater spectral resolution with 3 additional bands to SPOTs 4 multi-spectral bands. Landsat 7's new Enhanced Thematic Mapper Plus (ETM+) also draws closer to the SPOT 4 spatial resolution in many ways as it now also incorporates a panchromatic band that images the earth at 15m (SPOT Pan = 10m).

1.8 National Scale Assessment of TGDE Probability

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

Water levels (mbgl)	*Moisture growing season (Days)*					
		<25	*25-50*	*50-100*	*100-150*	*>150*
	Rating	*10*	*8*	*6*	*3*	*1*
0-10	*10*	100	80	60	30	10
10-20	*8*	80	64	48	24	8
20-30	*6*	60	48	36	18	6
30-50	*4*	40	32	24	12	4
50-70	*2*	20	16	12	6	2
>70	*1*	10	8	6	3	1

The data sets used to compile the map were:

- Water levels from Vegter's Groundwater regions of South Africa (1995)
- MGSD from Schulze (1997) South African Atlas of Agrohydrology and Climatology.

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 (eg. 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.]

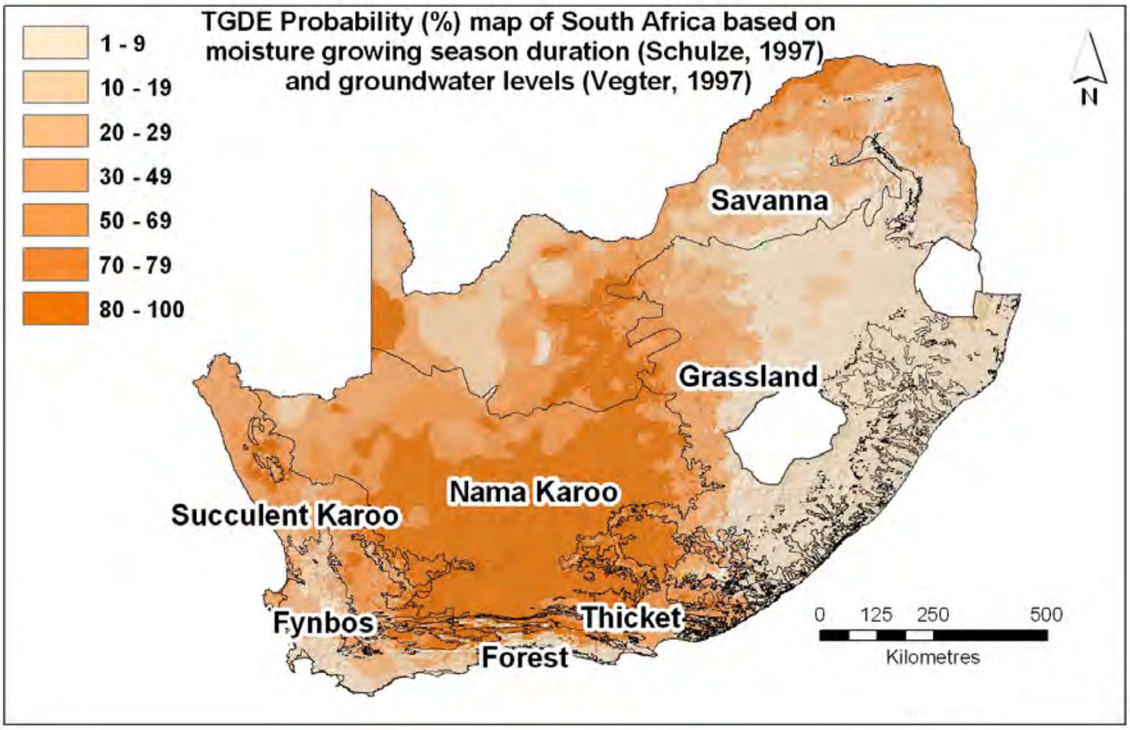


Figure 3: Probability of Terrestrial Groundwater Dependent Ecosystems based on Groundwater Levels (mbgl) and Moisture Growing Season Duration (days) for South Africa

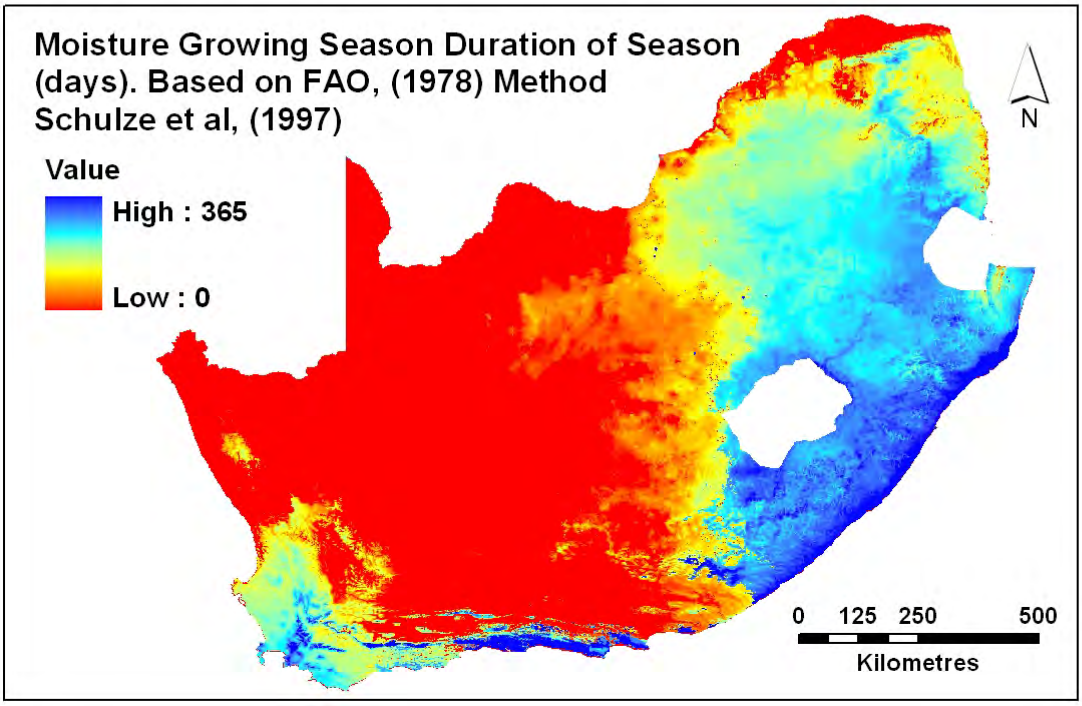


Figure 4: Mean groundwater levels in South Africa (Vegter, 1995)

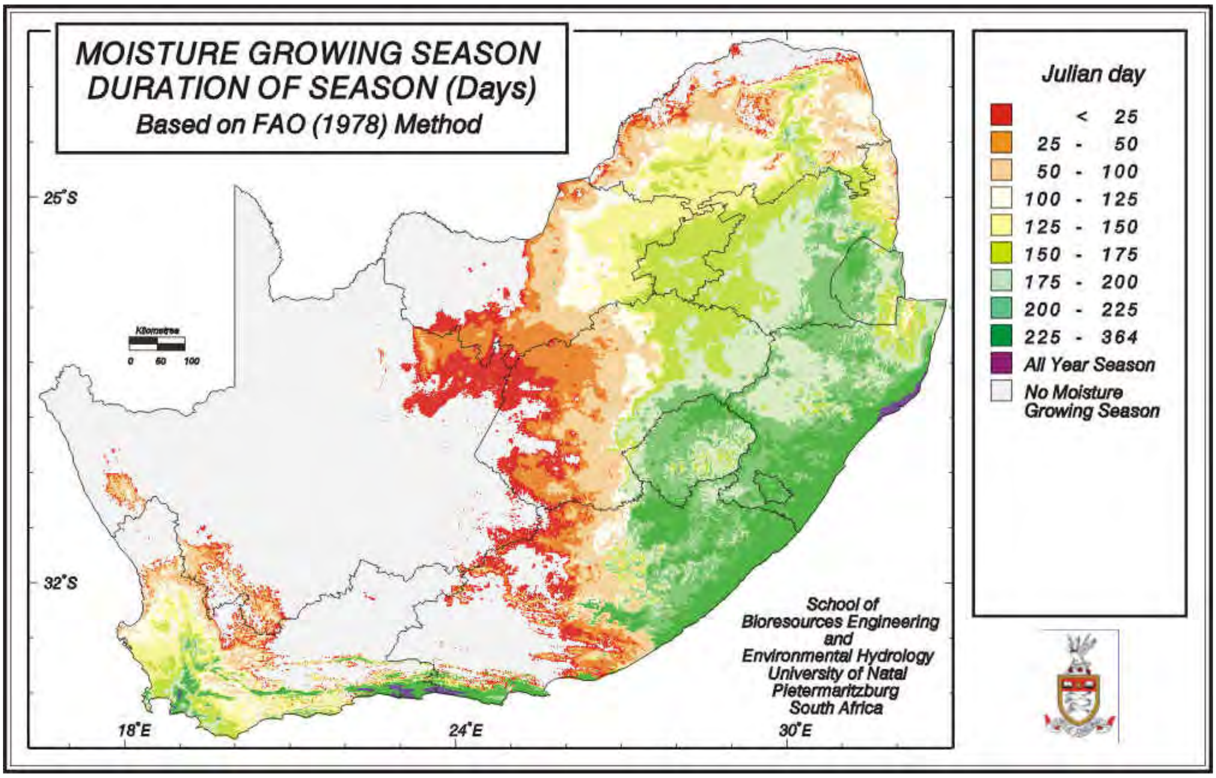


Figure 5: Moisture Growing Season Duration (days) (FAO, 1978 method as presented in Schultze et al., 1996)

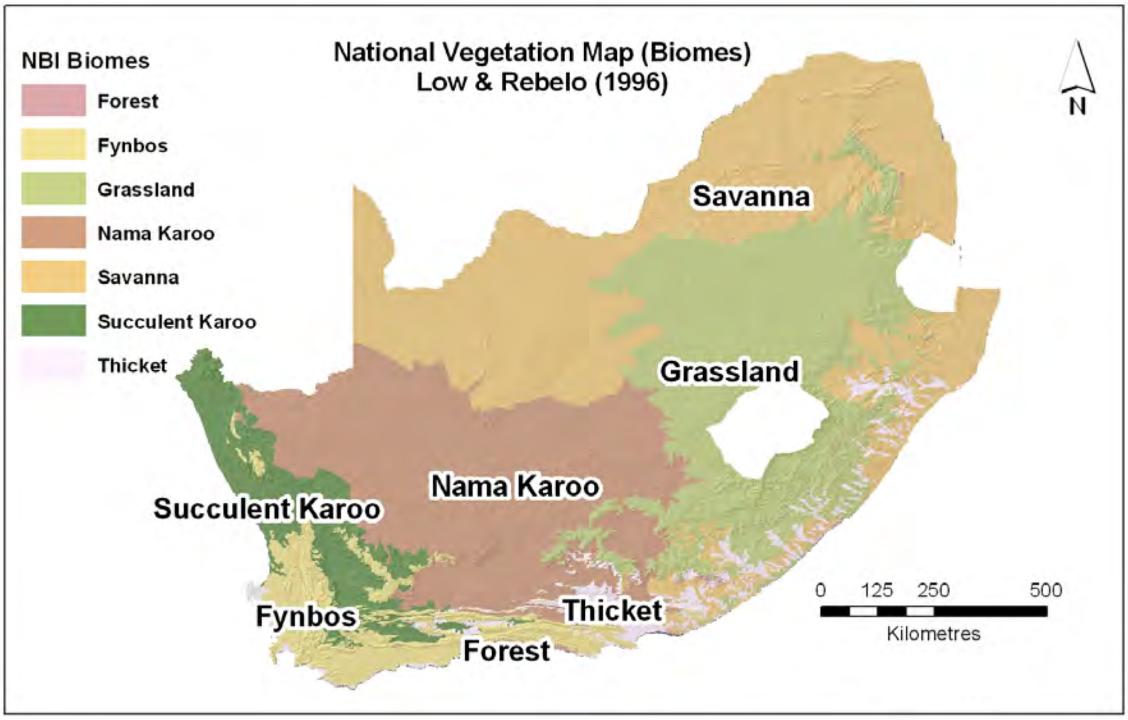


Figure 6: Biomes of South Africa (Low and Rebelo, 1996)

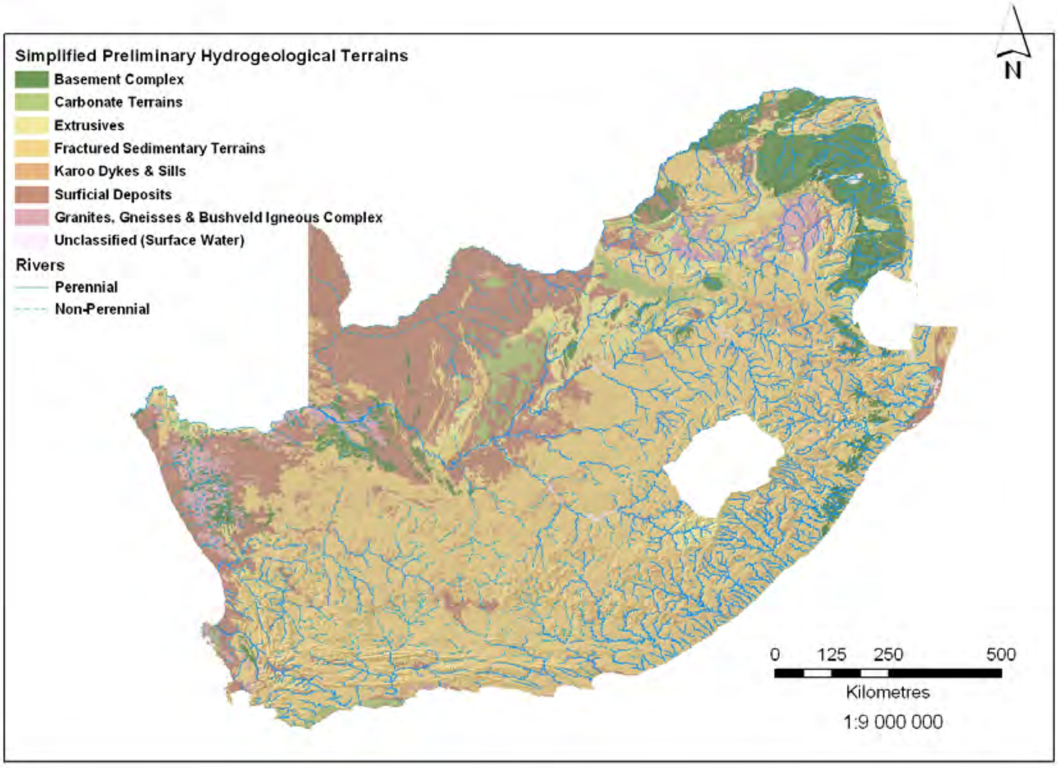


Figure 7: Simplified Hydrogeological Terrains of South Africa based on a grouping of primary lithology.

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 (Acocks, 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.

1.9.3 Hydrogeological type settings

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;

- Karoo dykes and sills;
- Fractured sedimentary (by far the largest terrain).

Suggested typesettings 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 type-settings described below are presented as cartoons where the important features are emphasised and other features are compressed to fit in the limited space available. In each case a full profile or cross-section has been shown in order to place the features into context. The specific features of each locality will, naturally, vary because of the localised geomorphological evolution of the landscape but the basic features illustrated in the diagrams should still be visible.

1.9.4 Fractured sedimentary terrains

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.

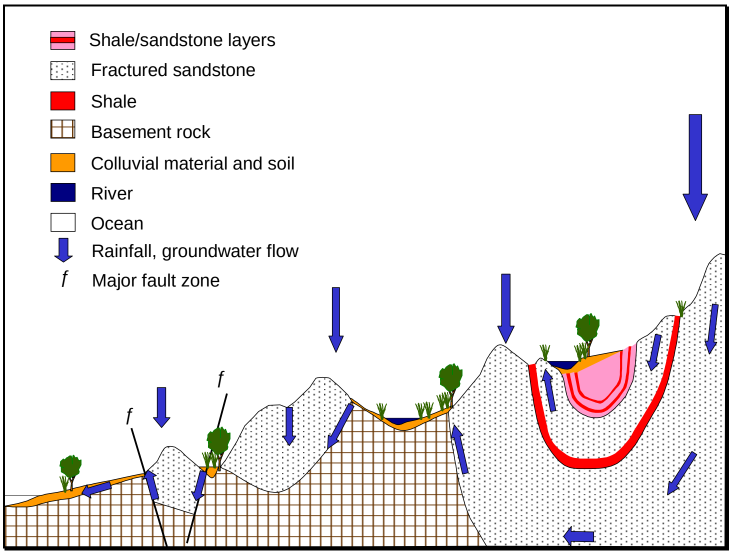


Figure 8: Fractured sedimentary terrain:
A typical Cape Supergroup geohydrological setting in the Cape Fold Belt. The major geological formations are dominated by the shales and quartzites of the Table Mountain Group. The flow paths of groundwater and the location of groundwater dependent ecosystems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

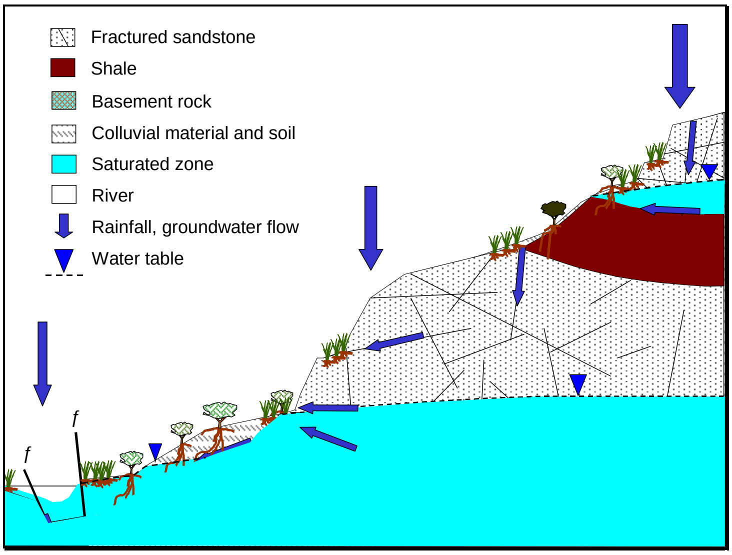


Figure 9: Fractured sedimentary terrain:
A typical Table Mountain Group geohydrological type-setting setting showing the major geological formations and the flow paths, likely discharge areas for groundwater and the associated groundwater dependent ecosystems.

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.

KAROO

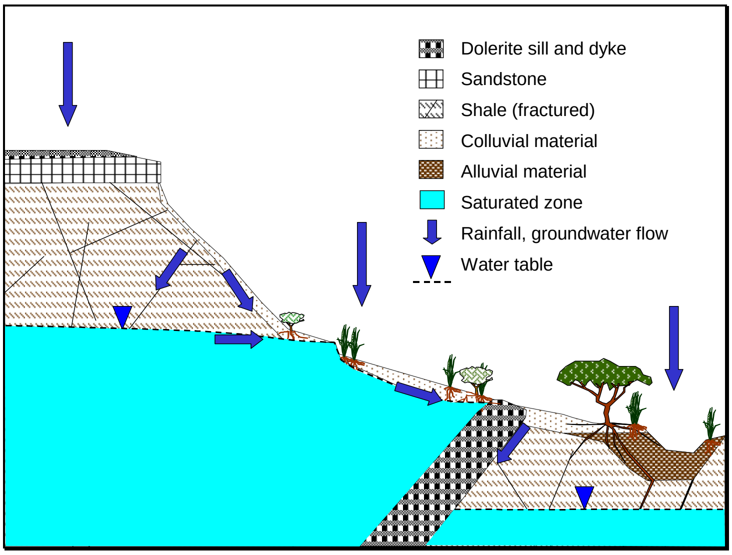


Figure 10: Fractured sedimentary terrain:
A cross-section of a Karoo inselberg or portion of the escarpment showing the major geological formations, the fluxes of groundwater and the likely location of TGDEs. The importance of the alluvial deposits to TGDEs would depend on the flow regime in the river.

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 which 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).

MPUMALANGA ESCARPMENT

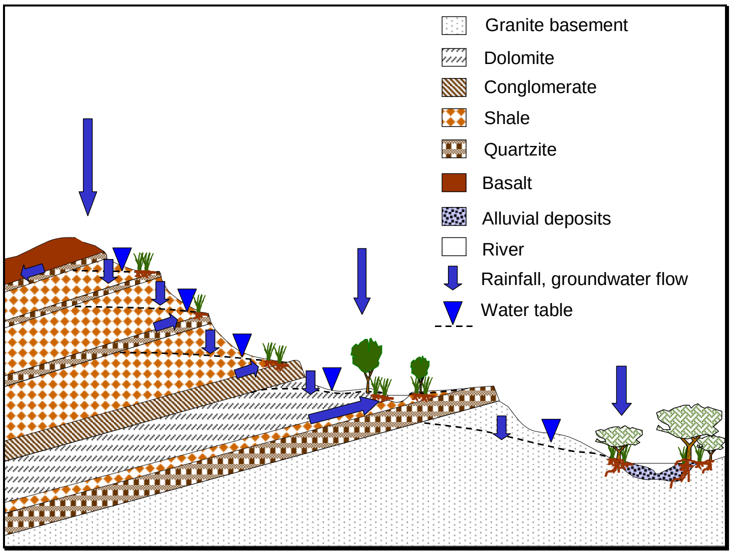


Figure11: Fractured sedimentary terrain:
A cross-section of the Mpumalanga escarpment near Mount Anderson showing the complex layering of the geological formations, the possible location of groundwater and the associated TGDEs. Note the presence of a dolomitic formation above the quartzites. The dolomites 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 overlying 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.

KWAZULU-NATAL DRAKENSBERG

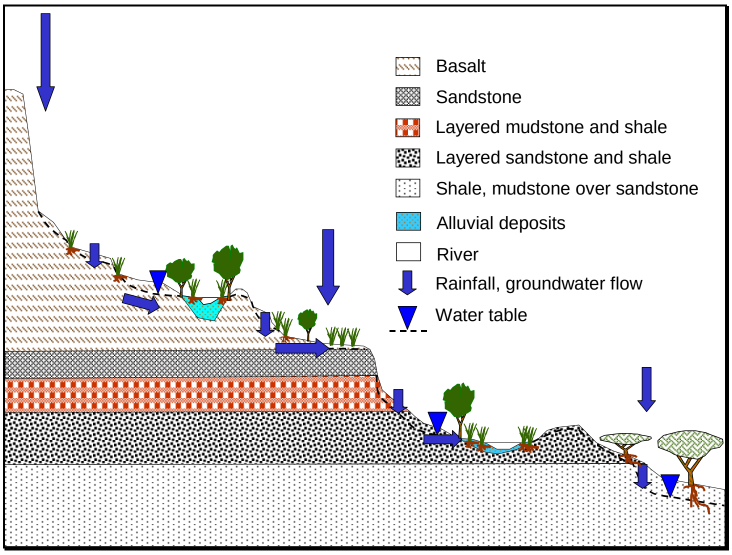


Figure 12: Fractured sedimentary terrain:
A similar section to that in Figure 11 showing the geological formations of the KwaZulu-Natal Drakensberg, the flows of groundwater and the likely location of TGDEs.

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.

1.9.5 Carbonate terrains

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.

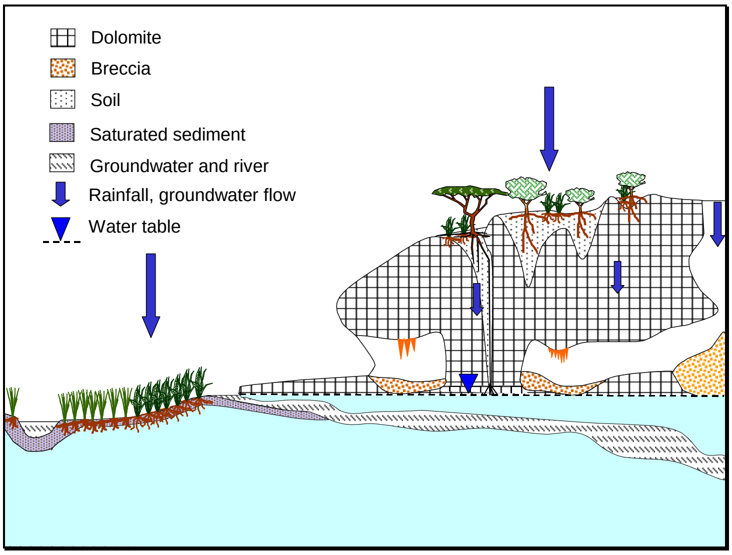


Figure 13: Carbonate terrain:
A cross–section of a karst formation illustrating the major geohydrological features and the location of groundwater dependent systems. The dolomites are easily weathered and have cracks which can be penetrated to great depths by the roots of deep-rooted species. The dolomites 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 intrduded 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 habitiats is groundwater dependent and results in cryptic discharge.

1.9.6 Granites, Gneisses and Bushveld Igneous Complex

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;

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

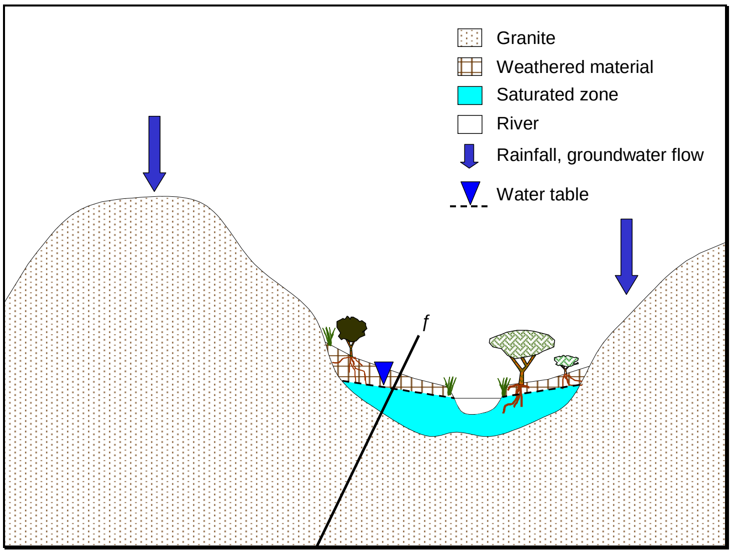


Figure 14: A granite terrain with accumulation of weathered colluvial and alluvial deposits.

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

1.9.7 Surficial deposits

COASTAL AND INLAND DUNE FIELDS

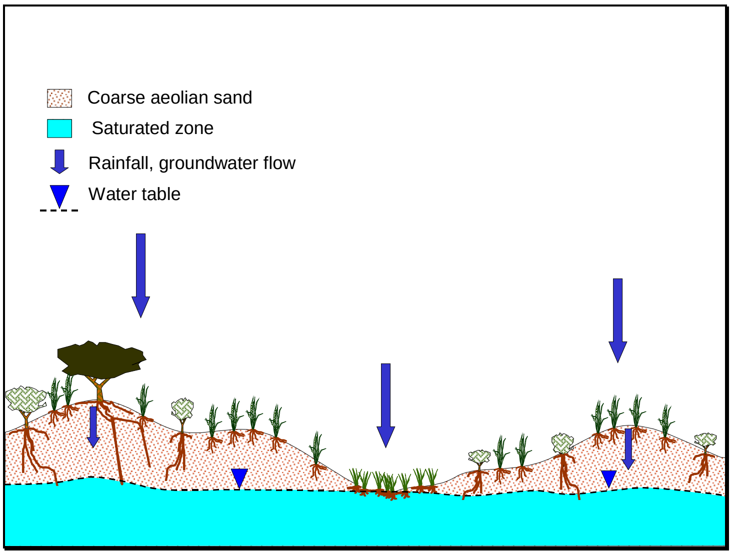


Figure15: Surficial deposit:

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 calcretes 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.

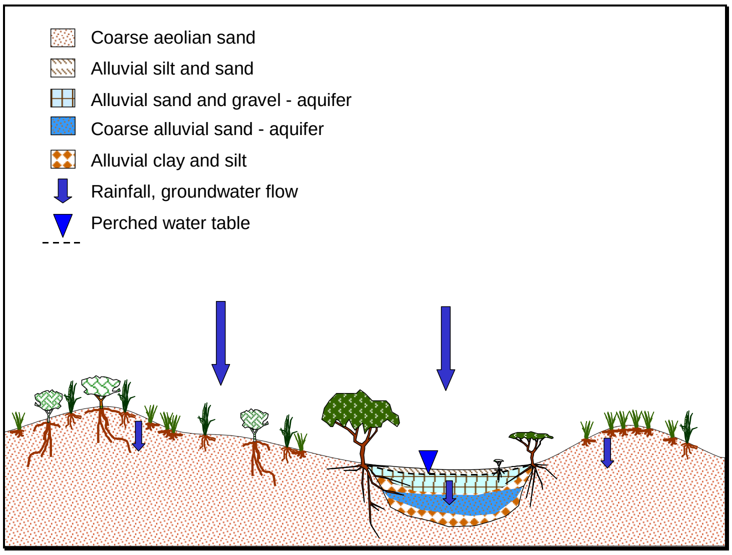


Figure 16 Surficial deposit:
A cross-section of an ephemeral river system in the deep sands deposits of the Kalahari Basin showing the layering of the alluvial sediments, perched storage off groundwater and deep rooting of the woody plants.

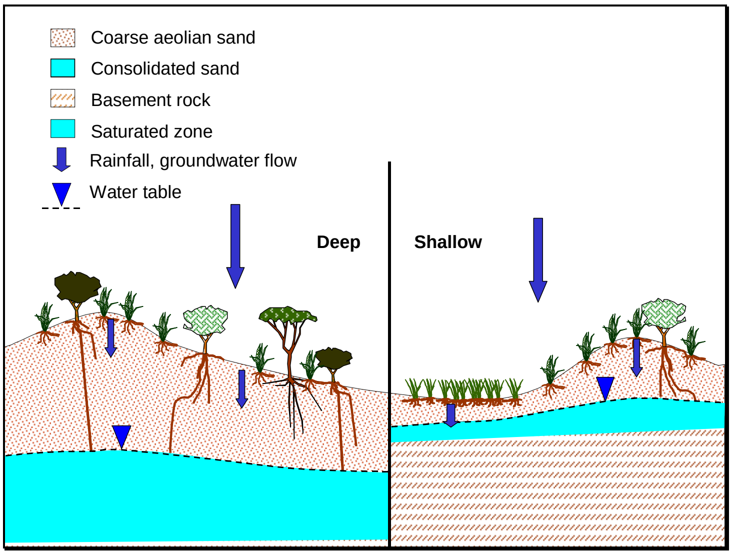


Figure 17 Surficial deposit:
Two cross-sections in the Kalahari Basin showing the deep sands, one where the depth of the sand, and to the water table, is relatively shallow and one where the groundwater is deeper. In both situations there would be no surface evidence of groundwater unless hydraulic lift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

Typesetting Summary

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.

Type setting	***Vegetation type and situation***	***Plant type or species***
Any	Most	Reeds: Phragmites australis, P. communis, Typha latifolia
Fractured sedimentary terrains and extrusives	Fynbos (Cape Supergroup, mainly Table Mountain Group quartzites and high-altitude and high-rainfall shales, montane and middle slope granites)	Restionaceae: Askidiopermum nitidum, Calopsis paniculatus, Cannomois virgata, Chondropetalum tectorum, Elegia capensis Sedges and grasses: Epischoenus gracilis, E. quadrangularis, Juncus krausii, Merxmuelllera cincta, Scirpus littoralis Others: Kniphofia uvaria, Osmitopsis asteriscoides, Wachendorfia thyrsiflora Trees and shrubs: Berzelia dregeana, B. intermedia, B. lanuginosa, Brunia alopecuroides, Brachylaena neriifolia, Cliffortia ferruginea, C. graminifolia, C. hirsuta, Empelurum serrulatim, Erica species, Leucadendron salicifolium, Metrosideros angustifolia, Osyris compressa, Psoralea affinis, P. aphylla, P. pinnata, Maytenus acuminata, Rapanea melanophloeos, Salix mucronata
	Renosterveld (granites and shales of lower slopes and lowlands)	Sedges and grasses: as above Trees and shrubs: Acacia karoo (in some areas), Buddleja saligna, Grewia species, Maytenus capitata, Olea europaea subsp. africana, Rhus species, Sideroxylon inerme
	Nama Karoo	Sedges and grasses: Cenchrus ciliaris, Cynodon incompletus, Digitaria species, Hyparrhenia hirta, Juncus species, Panicum stapfianum, Setaria neglecta, Sporobolus fimbriatus Others: Asclepias buchenavianus, Aridaria granuliflora, Convolvulus saggitatus, Deverra species, Frankenia pulverulenta, Helichrysum pentzioides, Lotononis listii, Protasparagus (Asparagus) africanus, Vahlia capensis Trees and shrubs: Acacia erioloba, A. karoo, A. mellifera, Diospyros lycioides, Euclea undulata, Grewia robusta, Lycium cinereum, Maytenus polyacantha, Parkinsonia africana, Rhigozum obovatum, Rhus species, Salix mucronata, Tamarix usneoides
	Grasslands and savanna (Mpumalanga and KwaZulu-Natal escarpment)	Sedges and grasses: Andropogon amethystinus, A. appendiculatus, Arundinella nepalensis, Carpha filifolia, Cympopogon validus, Eleocharis species, Hyparrhenia dregeana, Isolepis species, Juncus species, Mariscus congestus, Merxmuellera macowanii, Miscanthus species, Pennisetum species Pentaschistis tysonii, Scirpus ficinoides, Thamnocalamus tesselatus Others: Androcymbium longipes, Crassula gemmifera C. natans, Epilobium species, Geranium species, Kniphofia species, Ranunculus species, Sebaea species, Zantedeschia aethiopica Trees and shrubs: Buddleja species, Cliffortia species Diospyros species, Erica cooperi, Erica leucopeltera, Euclea species, Kiggelaria africana, Leucosidea sericea, Maytenus species, Myrica serratum, Polemannia montana, Rhus species
	Savanna (Mpumalanga and KwaZulu-Natal escarpment)	Sedges and grasses: Bothriochloa insculpta, Chloris gayana, Panicum deustum, P. maximum, Setaria woodii and other wetland species Trees and shrubs: Acacia albida, A. karoo, A. nigrescens, Combretum erythrophyllum, Diospyros species, Euclea species, Lonchocarpus capassa, Rhus species, Schotia brachypetala, Syzygium cordatum

Type setting	*Vegetation type and situation*	*Plant type or species*
Karst systems	Dolomites (western highveld)	Sedges and grasses: wetland species Trees and shrubs: Acacia caffra, Buddleja saligna, Celtis africana, Buddleja saligna, Combretum species, Grewia species, Kiggelaria africana, Maytenus heterophylla, M. undata, Rhus species, Ziziphus mucronata
Granites, Gneisses and Bushveld Igneous Complex	Succulent Karoo (Namaqualand)	Sedges and grasses: Aristida species, Stipagrostis species Others: Asclepias buchenaviana, Delosperma species, Felicia muricata, Kochia salsoides, Protasparagus species Trees and shrubs: Acacia karoo, Carissa haematocarpa, Diospyros species, Euclea undulata, Ficus cordata, Grewia robusta, Lycium cinereum, L. oxycarpum, Melolobium candicans, Maytenus polycantha, Pappea capensis, Rhigozum obovatum, Rhus species, Salix mucronata, Schotia species, Tamarix usneoides
	Savanna and grassland	See species lists for the other savanna and grassland settings
Surficial deposits	Dune thicket (Western and Eastern Cape)	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 inerme,
	Sand Plain fynbos (Western Cape)	Restionaceae: Askidiopermum nitidum, Chondropetalum tectorum Sedges and grasses: Epischoenus species, Juncus species, Scirpus species Trees and shrubs: Berzelia species, Brunia species, Erica species, Euclea species; Leucadendron species, Leucospermum species, Maytenus heterophylla, Olea species, Protea species, Psoralea affinis, P. aphylla, P. pinnata, Pterocelastrus tricuspidatus, Rhus species.
	Coastal Bushveld (Zululand coastal plain)	Sedges and grasses: Carex species, Cyperus species, Digitaria eriantha, Mariscus species, Panicum maximum, Schoenus species Others: Ballota africana, Chasmanthe aethiopica, Frankenia species, Galium tomentosum, Kniphofia sarmentosa, Melianthus comosus, Ranunculus multifidus, Zantedeschia aethiopica Trees and shrubs: Acacia karoo, A. robusta, Diospyros species, Euclea species, Mimusops species, Syzygium cordatum, Tarchonanthus camphoratus, Swamp Forest
	Arid savanna: ephemeral rivers (Kalahari Basin)	Trees and shrubs: Acacia erioloba, A. haematoxylon, A. karoo, A. mellifera, Boscia albitrunca, Buddleja saligna, Diospyros pallens, Euclea pseudebenus, E. undulata, Faidherbia albida, Grewia flava, Lycium hirsutum, Maytenus undata, Rhus species, Tamarix usneoides, Tarchonanthus camphoratus, Walafrida geniculata, Ziziphus mucronata

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 world wide 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

Technique	*SPOT Vegetation*	*Landsat Multi Spectral Scanner MSS*	*Landsat 4/5 TM (Thematic Mapper)*
Application	Environmental studies Agriculture monitoring Forest monitoring Global change studies	Landcover/ Vegetation/ Geological mapping	Landcover/ Vegetation/ Geological mapping
Measurable	Reflected radiation indication landscape and vegetation types. Chlorophyll for NDVI[3] (& other VIs)	Reflected radiation indication landscape and vegetation types Good for regional and large area estimates of Chlorophyll for NDVI[3] (& other VIs) Greenness Brightness Wetness – Tasselled Cap	Reflected radiation indication landscape and vegetation types Chlorophyll for NDVI (& other VIs) Greenness Brightness Wetness – Tasselled Cap
Availability	SAC	SAC Archive USGS EDC	SAC Archive EDC
Costs – capital operational	€120 (up to 1 million square km) €135 (from 1 – 4 million square km)	$210 per 185x180km scene	$4200 per 185x180km scene
Environmental constraints/suitability	2,250 x 2,250 km scene size produces images of vast areas (4840000km^2) Affected by cloud cover	Covers large area 185 x 185km (34225km^2). Affected by cloud cover	Covers large area 185 x 185km (34225km^2). Affected by cloud cover
Capacity required – skills, hardware and software	RS Skills Capable PC Image Processing Software	RS Skills Capable PC Image Processing Software	RS Skills Capable PC Image Processing Software
Time required to get meaningful results	2-4 days	1-2days	1-2days
Resolution Spatial	1km x 1km MS	80m Visible – IR	30m Visible-IR 60m Therm IR
Spectral	Blue: 0.43 to 0.47 µm Red: 0.61 to 0.68 µm Near-IR: 0.78 to 0.89 µm S.wave IR: 1.58-1.75 µm	Green: 500 – 600 nm Red: 600 – 700 nm R – NIR: 700 – 800 nm NIR: 800-1100 nm	6 V-IR 1 TIR 450 – 520 nm 520 – 600 nm 630 – 690 nm 760 – 900 nm 1550 – 1750 nm 10400 – 12500 nm 2080 – 2350 nm
Temporal	14 days, pointable sensor	16 days	16 days repeat pattern
Output – format and scale (and compatibility with other RDM components).	Digital, statistical and graphical Provincial/national	Digital, statistical and graphical Local - Catchment	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	Highly limited, if at all	Wide	Wide
Previous use worldwide	Limited	Wide	Wide
Summary recommendations	Specially designed to sense vegetation, but spatially too coarse for detecting smaller ecosystems. Very good for large synoptic views and cheap.	Good spectral resolution. Low spatial resolution. Good value mapping product.	Good spectral and temporal resolution. Good cost effective alternative for local scale mapping

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

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

Table 7 continued

Technique	*Conventional Aerial Photography*	*Airborne Digital and Hyper-spectral Scanners*	*Airborne Video*
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 operational	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

Technique	*Potential evaporation – Linacre model*	*Plant community evaporation: Bowen ratio/ Eddy Correlation*
Application	Estimating the potential evaporation for an area.	The two techniques are both used to estimate evaporation but differ in the details.
Measurable	Potential evaporation in millimetres for varying periods of time.	Total evaporation from an area of a homogenous plant community.
Availability	The equations are available in the published literature (Linacre, 1977); Schulze (1995) presents various versions and discusses their application locally.	The equipment is available from scientific instrument suppliers who have local agents in South Africa.
Costs – capital operational	Minimal costs of acquiring the data and doing the analysis. Calculations can be done on a normal computer in a spreadsheet.	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.
Environmental constraints/suitability	Suitable for getting a rough estimate of the maximum amount of water that could be transpired by vegetation with free access to water.	These 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.
Capacity required – skills, hardware and software	Ability to use a spreadsheet or write data analysis programmes.	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.
Time required to get meaningful results	Depends on the time required to get the relevant daily climate data.	The sampling should preferably be done over a period of 2-3 weeks in each season for a year.
Resolution	Suitable for estimating for areas of at least a few hectares.	Total evaporation in millimetres for an area of a few hectares (>4 ha)
Output – format and scale (and compatibility with RDM)	A rough estimate of the volume of water that could be transpired – suitable for a desktop or rapid estimate only.	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.
Conjunctive use	Would need to be combined with an estimate of the proportion of groundwater that is being used.	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.
Previous use in SA	It is a well known formula and is recommended by Schulze (1995) in preference to others like it.	See Savage *et al.,* (1997), Everson *et al.,* (1998).
Previous use worldwide	Not known	Widely used, see Unland *et al.,* (1998) and Valentini *et al.,* (1991).
Summary recommendations	Only suitable for desktop or rapid assessment.	These are generally accepted as the most accurate methods for measuring actual evaporation from relatively large areas (>4ha) of a homogenous vegetation community. Provides an integrated measurement of evaporation (i.e. all components are included).

Table 7 continued

Technique	*Plant community evaporation: infra-red measurement of canopy temperature*	*Plant community evaporation: Laser scintillometry*
Application	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.	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.
Measurable	Canopy transpiration losses.	Evaporation (transpiration and interception).
Availability	The equipment is available from scientific instrument manufacturers overseas- agent in SA.	Available from scientific instrument suppliers overseas.
Costs – capital operational	Cost of sensors varies from R500-R1500. Will require a weather station costing R15000 for modeling transpiration and scaling up to annual estimates. Operational costs likely to be low.	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 not known.
Environmental constraints/ suitability	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.	This must still be properly evaluated
Capacity required – skills, hardware and software	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.	Probably will require skilled technicians.
Time required to get meaningful results	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.	This technique will also require sampling across seasons to improve the accuracy of the estimated annual evaporation.
Resolution	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.	Potentially from metres to kilometres.
Output – format and scale (and compatibility with RDM)	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 estimates is acceptable for the level of reserve determination that is needed.	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 estimates is acceptable.
Conjunctive use	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.	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.
Previous use in SA	The equipment was recently imported into this country by the CSIR and still has to be tested thoroughly.	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.
Previous use worldwide	Used mainly in agricultural applications - Bartholic et al., (1972), Blad and Rosenberg (1976a), Blad and Rosenberg (1976b), Brown and Rosenberg (1973), Carlson et al., (1972), Choudhury et al., (1986),	Hill *et al.,* (1992), Hill (1997) and many ofther paprs by Hill and others, Choudhuri *et al.,* (1998).
Summary recommendations	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.	This is a very promising technique but still a couple of years from practical use in South Africa.

Table 7 continued

Technique	*Lysimeter studies on shallow groundwater*	*Multi-electrode resistivity*	*Isotope measurements*
Application	Intensive research determination of hydrological processes within a particular (and by implication) important plant community.	Resistivity is dependent on soil moisture, soil type, etc. Resistivity/ changes in resistivity with time can be indirectly related to soil moisture/soil moisture changes and groundwater.	This technique provides a direct measurement of groundwater use by the plant. It can indicate the proportion of groundwater used and seasonal variations.
Measurable	Direct measurement of water fluxes in saturated and unsaturated zones, and derivation of evaporation by mass balance.	Resistivity of the subsurface/changes in resistivity of the subsurface over time	$\delta^{18}O$ ‰ δD ‰ (SMOW) of water in xylem tissue.
Availability	Highly specialized equipment, but is readily available.	Equipment, software and operator is available from CSIR, Stellenbosch	Analysis can be carried out in Pretoria (CSIR, UCT and Wits University). Courier samples.
Costs – capital operational	High costs associated with intensive and long term studies: costs of installation engineering & equipment (load cells, soil water sensors, data loggers) are roughly R300 000 and would be associated with large human resource costs.	Use of equipment: R1500/day Operator: R2500/day Other running, e.g. S&T: variable	Cost of boreholes to sample groundwater if not established. Analysis: ^{18}O and δD in water R150 & R200, plus R50 if extracted from sapwood. Min 3 samples/ plant.
Environmental constraints/suitability	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).	Resistivity contrast between unsaturated and saturated zone. Will not work with highly resistive surficial layer.	Significant contrast in $\delta^{18}O$ ‰ or δD ‰ between groundwater and other sources of water.
Capacity required – skills, hardware and software	Specialised research skills in agricultural or botanical water research; associated with modern high-tech instrumentation skills.	Trained geophysicist to acquire field data, process and interpret data. Multi-electrode resistivity equipment and resistivity inversion software.	Field technicians capable of careful sampling. Isotope analysis and interpretation.
Time required to get meaningful results	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.	Immediate data acquisition, processing and analysis: 3 days per 2 linear km. Time lapse measurements every two weeks for first 6 months	Once off sampling – 1 week. Seasonal sampling – 1 year.
Resolution	Community level information is derived from a micro-plot (1 m^2).	Shallow subsurface (root zone). Variations with time.	Plant level, variations with time.
Output – format and scale (and compatibility with other RDM components	Full water balance is produced for community represented by the plants in the lysimeter.	Resistivity change due to groundwater use of plants. Soil moisture measurements should be used to calibrate measurements. Also relate to plant transpiration.	Indication of total or proportional groundwater dependency.
Conjunctive use	Other detailed monitoring, such as of weather, would complement a lysimeter study, to make full use of the investment at the site.	Calibrate with soil moisture, plant type, soil type, transpiration, etc. measurements.	Upscale using measurements of transpiration or RS.
Previous use in SA	Primarily at Agricultural research stations, and not in relation to groundwater (e.g. Snyman, 19XX, Everson *et al., 1*996)	Mineral exploration (Miningtek, CSIR)	Used in forestry and riparian studies.
Previous use worldwide	Commonly used, but not to assess groundwater interactions with vegetation.	Widely used: Barker *et al.,* (1992 – recent) Ackworth *et al.,* (1992 – recent) Loke *et al.,* (1995 – recent)	Used quite widely, mainly for forestry.
Summary recommendations	Research technique suitable for high profile, special cases requiring detailed understanding.	Groundtruth/calibration very important for unique solutions. Rapid data acquisition and interpretation. Time lapse data can be used to indicate changes with time.	Important confirmation of groundwater use where an isotopic contrast exists. Can give quantitative results varying with time. First indication within 1 week.

Table 7 continued

Technique	*Rubidium and other artificially applied chemical tracers.*	*Chemical "finger-printing" to identify sources of water in plants and surface flow.*	*Modelling of dynamic interaction between groundwater and vegetation communities.*
Application	This technique provides a direct qualitative measurement of groundwater use by the plant	Identification of sources of water used by plants, and the relative contributions of the various sources.	Detailed process modelling of vegetation groundwater interactions using an appropriate process model.
Measurable	Rubidium concentration in tissue of transpiring leaves.	Chemical characteristics of different water sources of water.	Model predictions of several key variables against which model performance can be verified.
Availability	Analysis carried out at ARC labs in major centres. RbCl available from scientific suppliers.	Moderately accessible technique.	Numerous models are available. Choosing the appropriate model is critical, and is determined by nature of system and important variables of interest.
Costs – capital operational	Cost of injection boreholes if not established. RbCl R400, plus standard ≈ R150. Analysis R26/sample. Min 3 samples/ plant.	Water chemistry and stable isotope laboratories already exist.	The major cost is in terms of human resources; in learning to understand the model, populate it and calibrate it against measured data..
Environmental constraints/suitability	Plant roots must intercept injected tracer flow. Amount of tracer to inject may be difficult to determine.	Need to understand and be able to sample the various water sources in a particular situation.	Few. The system needs to be understood adequately for an appropriate model to be chosen, and sufficient input data would need to be available.
Capacity required – skills, hardware and software	Plant tissue analysis.	Hydrological, water chemistry and isotope chemistry skills.	Specialised geohydrology and soil water hydrology knowledge, and computer skills.
Time required to get meaningful results	Need at least 2 months for Rb levels to build up.	Relatively quick. One to a few months study.	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.
Resolution	Plant level.	Essentially a landscape (hydrological unit) scale technique.	Depends on the model, and need not be constrained.
Output – format and scale (and compatibility with other RDM components	Indication of groundwater use, but not in proportion to total use.	Numeric; quanitification of contribution of water sources. Essentially a landscape scale.	Typically numeric, digital and possibly statistical outputs.
Conjunctive use	Upscale using measurements of transpiration or RS. Indicate proportional use of groundwater with transpiration measurements and water balance.	To be used with botanical and hydrological techniques to build complete, quantified water balance picture.	Only reliable when model is associated with calibration with observed data, and preferably when done on a study site.
Previous use in SA	Used in limited forestry studies.	Uncertain; probably quite common in groundwater studies.	Reasonable amount of work, but no focussed work on vegetation and groundwater interactions; no consensus on models.
Previous use worldwide	Very little documented evidence of use.	Limited use. Paper by Mengis *et al.,* (1999) used as type for this description.	Widespread, with reasonable success where appropriate models are used in association with a detailed study of the real system.
Summary recommendations	Gives qualitative confirmation of groundwater use. Cannot indicate variation with time. Needs at least 2 months.	Useful where complex water sources are available to vegetation communities.	Modelling is a necessary development to accompany studies, but not replace them, and allows extension of learning to broader scale and other regions.

Table 7 continued

Technique	*Monitoring of plant response to water table declines*	*Chloride balance modeling*
Application	Development of management guidelines from direct studies of plant responses to groundwater utilization	Measuring vertical fluxes of water (capillary rise and drainage) in the unsaturated soil (root zone).
Measurable	Numerous plant growth and health parameters in association with groundwater monitoring, e.g. growth rate, branch die-back, tree mortality, seedling recruitment.	Chloride concentrations in soil extract, soil and irrigation & ground-water, and water balance components (rainfall, drainage and irrigation).
Availability	Relatively simple and readily available equipment: water monitoring with piezometers (automatic or otherwise) and some plant physiology equipment.	Readily available. Requires standard soil science laboratory equipment.
Costs – capital operational	Costs: relatively modest, depending on the precise experimental design, using readily available equipment and monitoring methods.	Low capital costs. Relatively intensive sampling and monitoring regime.
Environmental constraints/ suitability	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.	Probably dependent on reasonable salinity gradients. Suitable for saline soil zones with a shallow water table where groundwater can rise into the rooting zone.
Capacity required – skills, hardware and software	Capability to monitor the plant response to stress (biological skills). Groundwater monitoring.	Soil chemistry and laboratory skills.
Time required to get meaningful results	Longer term research, usually a minimum of one hydrological year.	One to two year study to obtain a balanced picture.
Resolution	Need at least two sites which can be treated independently (abstractions will affect one and not the control site).	Essentially a plot scale method. Usually several sampling points would permit scaling up to the landscape scale with similar groundwater situation exists.
Output – format and scale	Digital, statistical (e.g. survival statistics) and descriptive. The outputs are plant growth and health criteria. Local catchments – landscape scale.	Numeric.
Conjunctive use	Suitable for use together with all other approaches.	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.
Previous use in SA	Interesting example on the Limpopo River, with the water supply for Venetia Mine (DeBeers, nd)	None known
Previous use worldwide	Widely used, particularly in the southwestern USA.	Saline soils in Australia and irrigation on the plains of the Indus River, Pakistan.
Summary recommendations	Sound approach appropriate for situations where shallow groundwater is being or is going to be utilized.	A useful technique for quantifying vertical water fluxes as part of quantifying the water balance and dynamics of vegetation communities on shallow groundwater.

Table 7 continued

Technique	*Moisture stress*	*Xylem analysis*	*Carbon-13 isotopes to indicate plant stress history*
Application	Measures the degree of moisture stress a plant is experiencing.	Screening woody plant species for susceptibility to changes in groundwater availability.	Stable carbon isotope ratios can be used to identify the history of water stress in trees
Measurable	The hydraulic tension in the plants water conducting tissues at a point in time.	Susceptibility to the formation of embolisms in conducting tissues.	In times of high water stress it is anticipated that trees will form tissue at a slower rate, and that the tissue will have a higher ratio of 13C/12C than in times of reduced water stress.
Availability	Specialist suppliers or could be manufactured by from plans. Organizations such as the ARC, NBI and several universities have the necessary equipment.	Cannot be purchased off-the-shelf at present. Botany departments at universities may do this.	CSIR (Quadru) laboratory in Pretoria; and potentially also UCT.
Costs – capital operational	Costs of purchase probably less than R10 000. Other costs primarily for field work and running costs such as supplies of full gas cylinders.	Not known but the capital costs should be quite low. Other costs primarily for field work and running costs.	13C in plant material - R260 + R150 for cellulose extraction (optional but recommended) per sample. Works by comparison of stress over time so many samples are need (minimum of ten?)
Environmental constraints/ suitability	Best used for screening in areas where the plant species are expected to require groundwater.	Most suitable for investigating woody plant species in semi-arid to arid areas where severe (seasonal) moisture stress is likely.	Trees have to be readily aged and preferably have clear year rings; a degree of dendrochronology work is required on the plants.
Capacity required – skills, hardware and software	Robust and simple to use provided the right precautions are taken. Experience is needed to become proficient and to get consistent and repeatable observations.	A technician or plant wood anatomy graduate student. A spreadsheet could be used to summarise the data (Pammenter and van der Willigen, 1998).	Expertise in the specialised laboratory routines is the main constraint. Specialised laboratories and staff skilled in the carbon isotope and cellulose extractions.
Time required to get meaningful results	Sampling both in the wet season and at the height of the dry season to determine seasonal variation - at least 6 months.	This depends mainly on the time required to get the samples and test them and the availability of the equipment.	2 months or more, depending on suitability of the woody species involved.
Resolution	Plant species and their habitats.	Plant species and the communities or habitats in which they occur.	Site level studies to represent landscape types. Individual trees or plants are analysed in different landscape positions.
Output – format and scale	A description /map showing the distribution of the indicator species and their associated habitats.	A description /map showing the distribution of the indicator species and their associated habitats.	Compatible with other site level studies, and will complement most investigations of water sources and their relative use by plants.
Conjunctive use	Source of water, water balance and transpiration measurements.	Need to distinguish the source of the water in the plant, or the tissue composition, and measure transpiration rates.	Use together with studies of plant water use through seasons.
Previous use in SA	Used in plant ecophysiological research for more than 20 years – (Smith, 1990), Richardson and Kruger (1990)	Botany Department at the University of Natal (see Pammenter and vander Willigen, 1998).	Tested at the moment by the CSIR, and now being used in preliminary WRC study.
Previous use worldwide	Widely used for more than 25 years. See Ritchie and Hinckley (1975), Nilsen *et al.,* (1984) and Sala *et al.,* (1996).	Plant ecophysiological research, especially in Mediterranean and desert ecosystems. See Davis & Mooney (1986), Pockman and Sperry (1997)	Fairly new, but well established in studies.
Summary recommendations	Can assess whether plants have free access to water and affects of changes.	A promising technique potentially worth pursuing as a research project.	May be limited to relatively few species, but it has strong advantages in cost and time.

Table 7 continued

Technique	*Whole plant transpiration*	*Leaf and shoot transpiration*
Application	Measurements of whole plant water-use based on sap-flow coupled with measurements of climatic variables.	Water loss through transpiration from a single leaf or a small cluster of leaves.
Measurable	The transpiration of an individual plant, usually woody, expressed as a volume or converted to a depth (mm).	Transpiration by single leaves or small shoot with a few leaves.
Availability	The equipment is available from suppliers of scientific equipment and there are agents in South Africa.	Commercially available from specialist instrument suppliers. Versions of the instruments are described by Schulze *et al.,* (1982) and Field *et al.,* (1982).
Costs – capital operational	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.	Capital - R30K. Instruments are delicate and require lots of maintenance. The associated weather station would cost about R15K. Operating costs – travel and field accommodation.
Environmental constraints/suitability	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.	Best suited to estimating transpiration for stands of a single species, or mixed species stands if all the important species are measured.
Capacity required – skills, hardware and software	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.	The instruments require trained operators. Interpretation and modelling of the data requires substantial experience and a sound understanding of plant ecophysiology.
Time required to get meaningful results	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.	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.
Resolution	The output is the volume of water transpired by a sample of plants and can be expressed per unit area.	Strictly the leaf or shoot but there are procedures for scaling up to the whole canopy and to a community.
Output – format and scale (and compatibility with other RDM components	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	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
Conjunctive use	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.	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.
Previous use in SA	Dye and Olbrich (1993), Dye *et al.,* (1992), Smith (1992), Smith *et al.,* (1992).	Used research organisations but not yet in studies of groundwater dependence. Richardson and Kruger (1990), Smith (1990).
Previous use worldwide	Widely used. Ansley *et al.,* (1994) and Howard *et al.,* (1997) .	Widely used. Nilsen *et al.,* (1984) and Sala *et al.,* (1996).
Summary recommendations	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.	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.

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 farm lands, 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.

Reference: Khanzada *et al.,* (1998) 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.

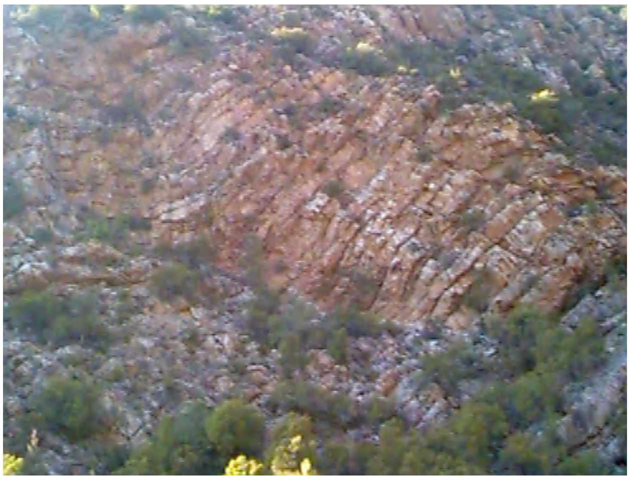
Reference: Midgley *et al., 19*94

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.

Figure A1. Field Site Location

The topography is broken by deep ravines formed by the major rivers that run along fault lines. Southern slopes are steeper than northern slopes.

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° (July) (Richardson, *et al., 1994*).

The geology is dominated by an upper (Nardouw) and lower (Penisula) 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., 19*94).

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., 19*94).

Groundwater dependent vegetation is thought to occur in fault controlled riparian zonez 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.

[1] *ArcGIS – a suite of GIS software produced by Environmental Software Research International (ESRI). http://www.esri.com/*
[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 +)
- SPOT 4 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:

$$\text{NDVI} = \frac{\text{Near Infrared} - \text{Red}}{\text{Near Infrared} + \text{Red}} \qquad \textit{Equation A1}$$

(Adapted from Lillesand, *et al., 19*94)

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 the 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-permeability, 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 8bit 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-1B0000_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 [5]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 A1: Landsat TM & ASTER VNIR spectral characteristics

	Band	Landsat 7 ETM+ (nm)	Band	ASTER (nm)
Blue	1	0.45 – 0.52		
Green	2	0.52 – 0.60	1	0.52 – 0.60
Red	3	0.63 – 0.69	2	0.63 – 0.69
Very Near Infrared	4	0.76 – 0.90	3	0.76 – 0.86

[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:

$$NDVI = \frac{Band\ 4 - Band\ 3}{Band\ 4 + Band\ 3} \qquad \textit{Equation A2}$$

It will now read:

$$NDVI = \frac{Band\ 3 - Band\ 2}{Band\ 3 + Band\ 2} \qquad \textit{Equation A3}$$

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 with in order to draw the data into a common framework.

Weightings

NDVI (no units)

Original values	*Weighting*
0 - 120	0
120 – 150	0
150 – 170	5
170 - 230	10

Geology

Original values	*Weighting*
Sedimentary	1
Shale	2
Conglomerate	4
Quartzite	10

Lineament Density (per 50m cell)

Original values	*Weighting*
0	0
0 – 1.5	3
1.5 – 3	6
3 – 5	10

Lineament Connectivity (per 50m cell)

Original values	*Weighting*
0	0
0 - 0.000001083	1
0.000001083 - 0.000003966	3
0.000003966 - 0.000005950	5

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.

A5. 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).

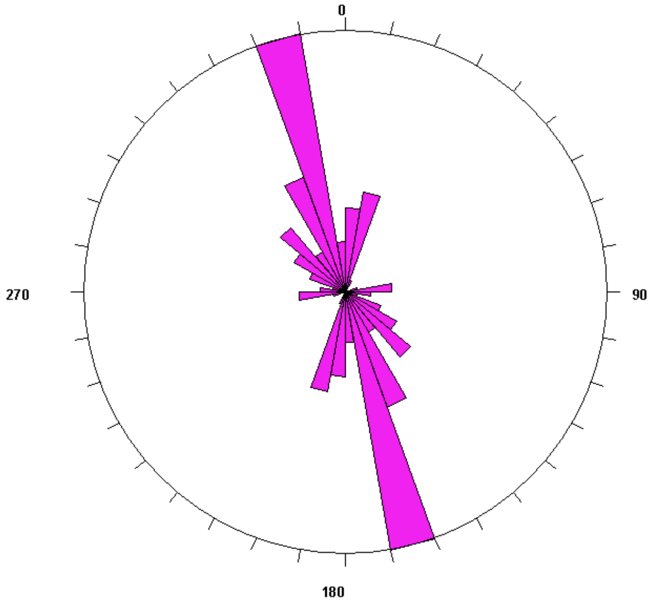


Figure A2. Rose diagrams for lineaments on study site A.

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 7 728m.
- 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

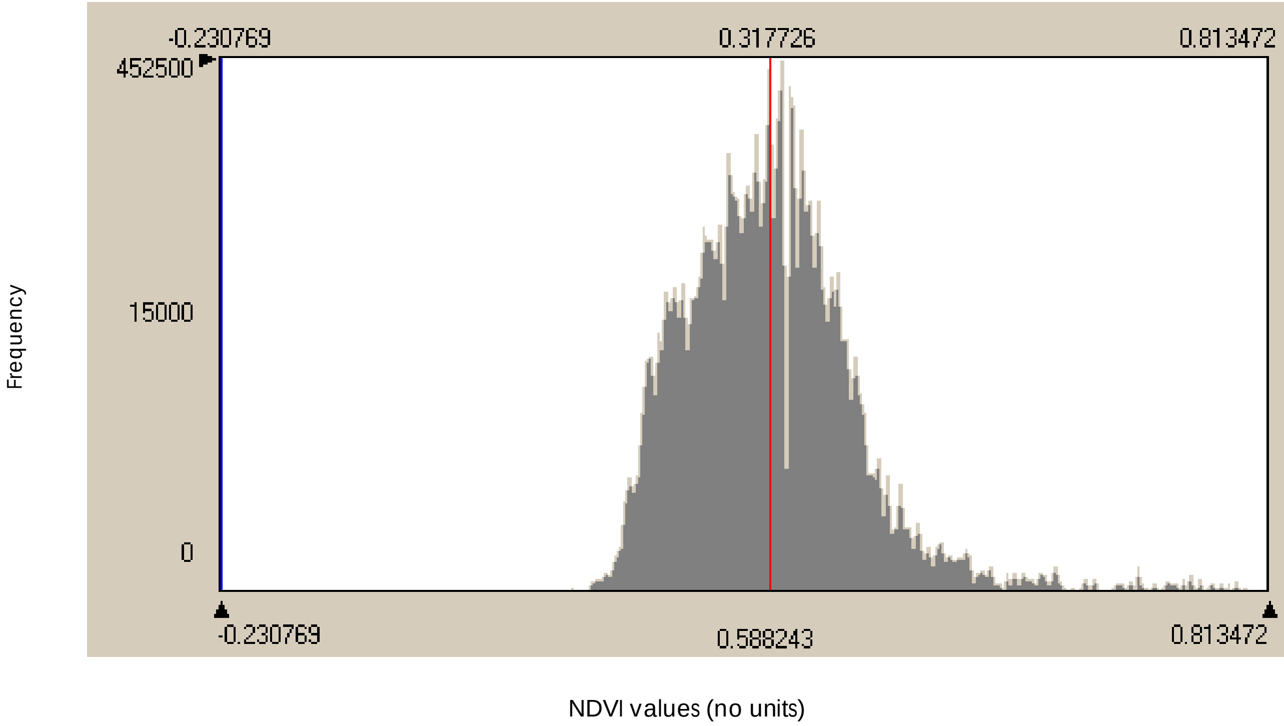


Figure A3: Histogram of NDVI values.

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 Vermaaksrivier and Moolenaarsrivier 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 and 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

Name	*Scale*	*Source*
GIS		
Rivers	1 : 50 000	Surveyor General
Quaternary Catchments	1:1 000 000	WRM90
Roads	1 : 1 000 000	Surveyor General
Geological Lineament	1 : 50 000	CSIR
Geology	1 : 1 000 000	Council for Geoscience
Imagery		
ASTER image PR-1B0000_2000110702_009_011 Captured 12 – 12 – 2001		USGS EROS Data Centre

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 chose for the project.

GIS links

DTM Consulting – creators of ArcView extension GeoTools http://www.dtmgis.com

ESRI – http://www.esri.com

ADDENDUM A3

DETAILED PROCESS DIAGRAM

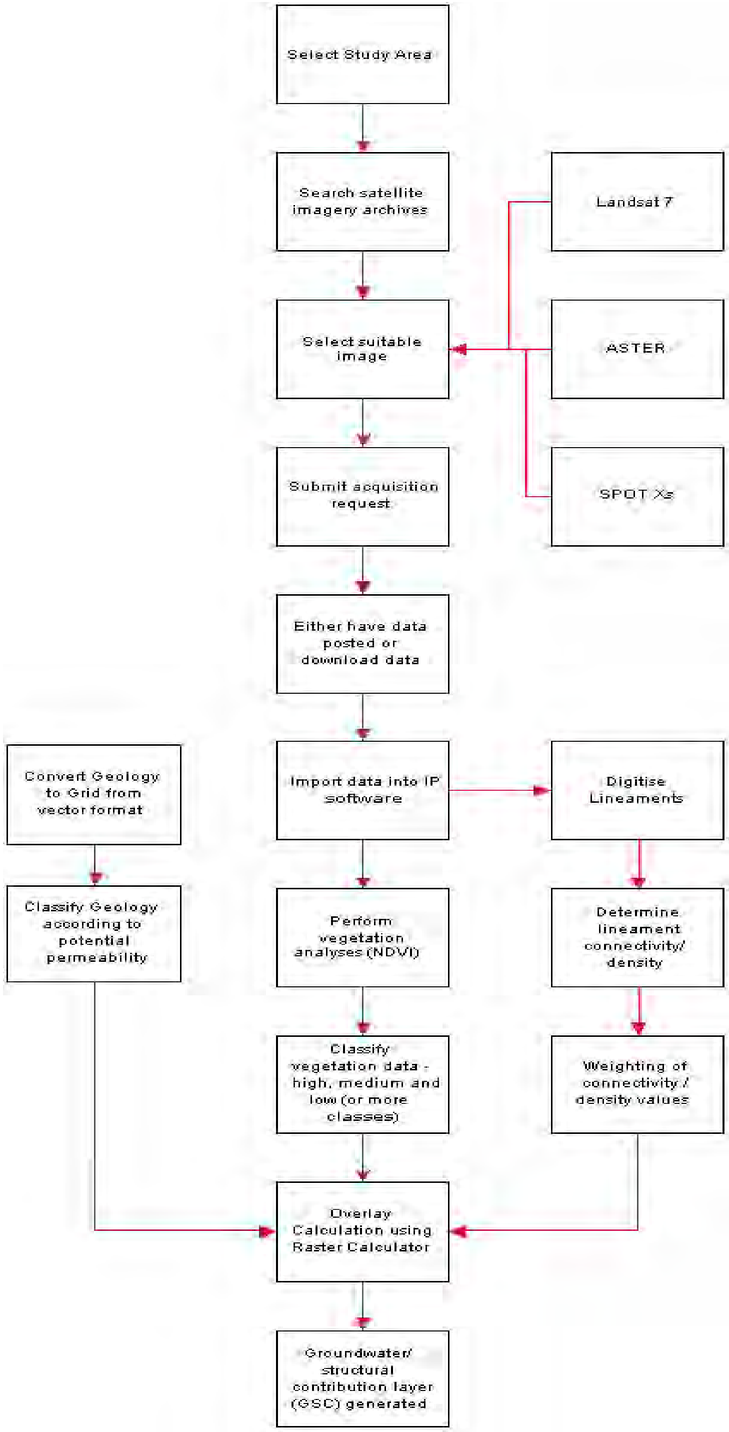


Figure A5

ADDENDUM A4

SUPPORTING FIGURES

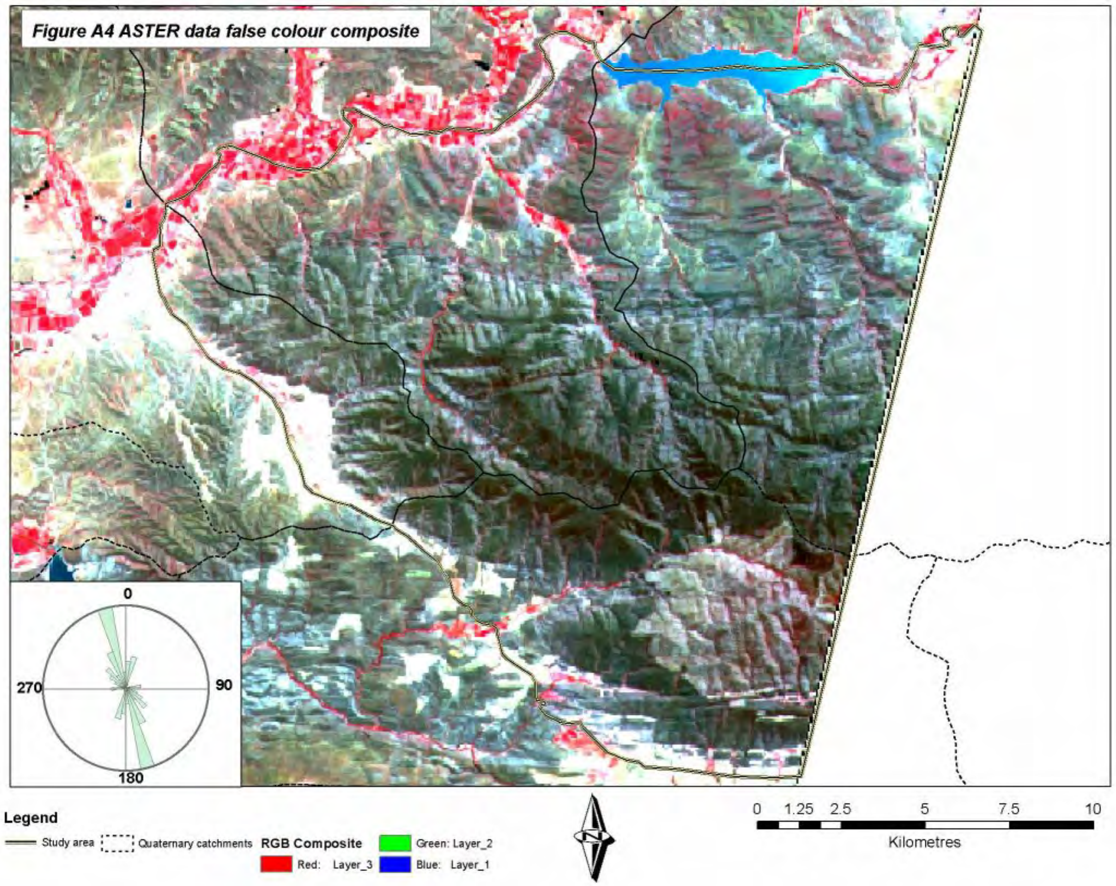


Figure A4 ASTER data false colour composite

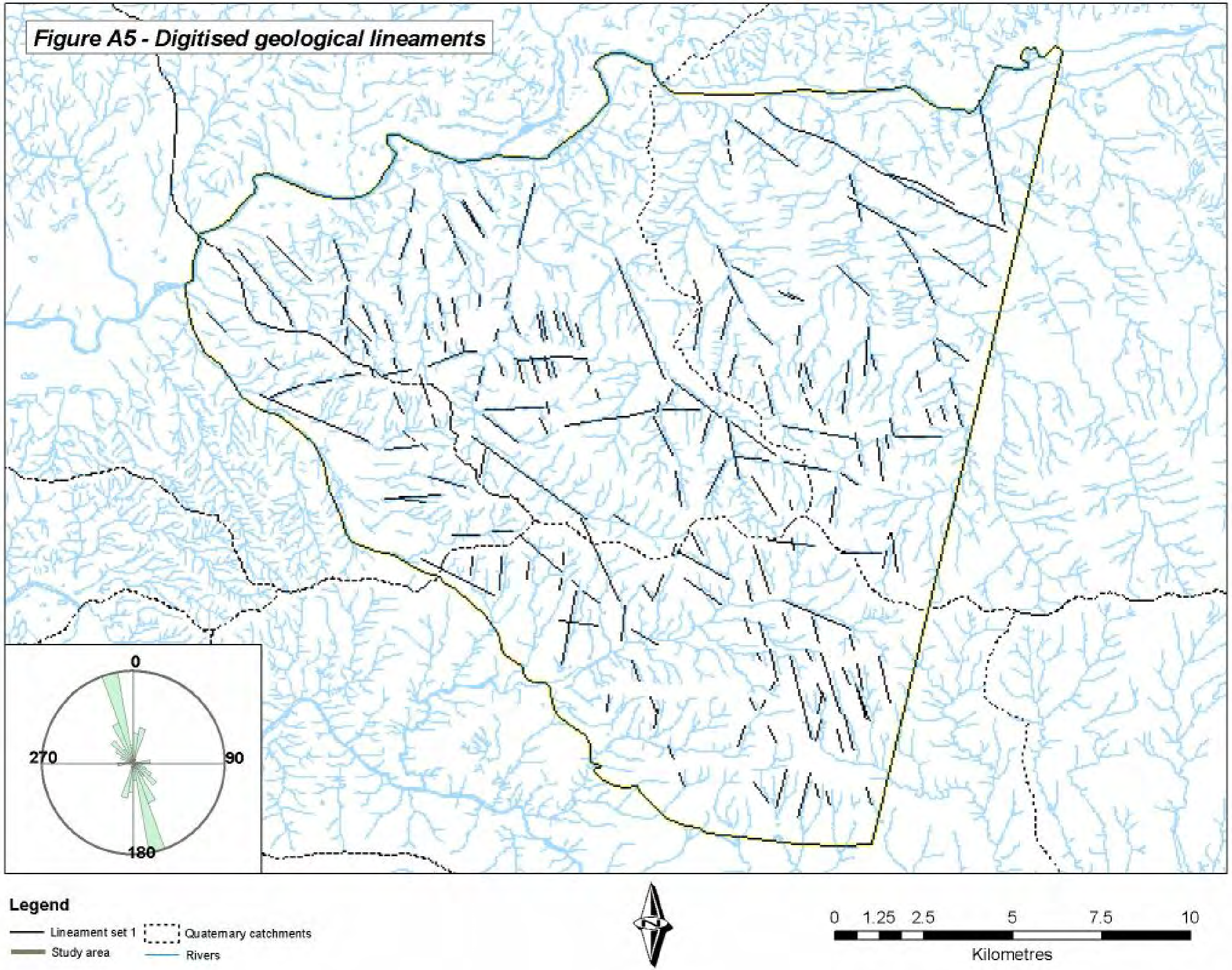


Figure A5 - Digitised geological lineaments
0
90
180
270
Legend
Lineament set 1
Study area
Quaternary catchments
Rivers
0
1.25
2.5
5
7.5
10
Kilometres

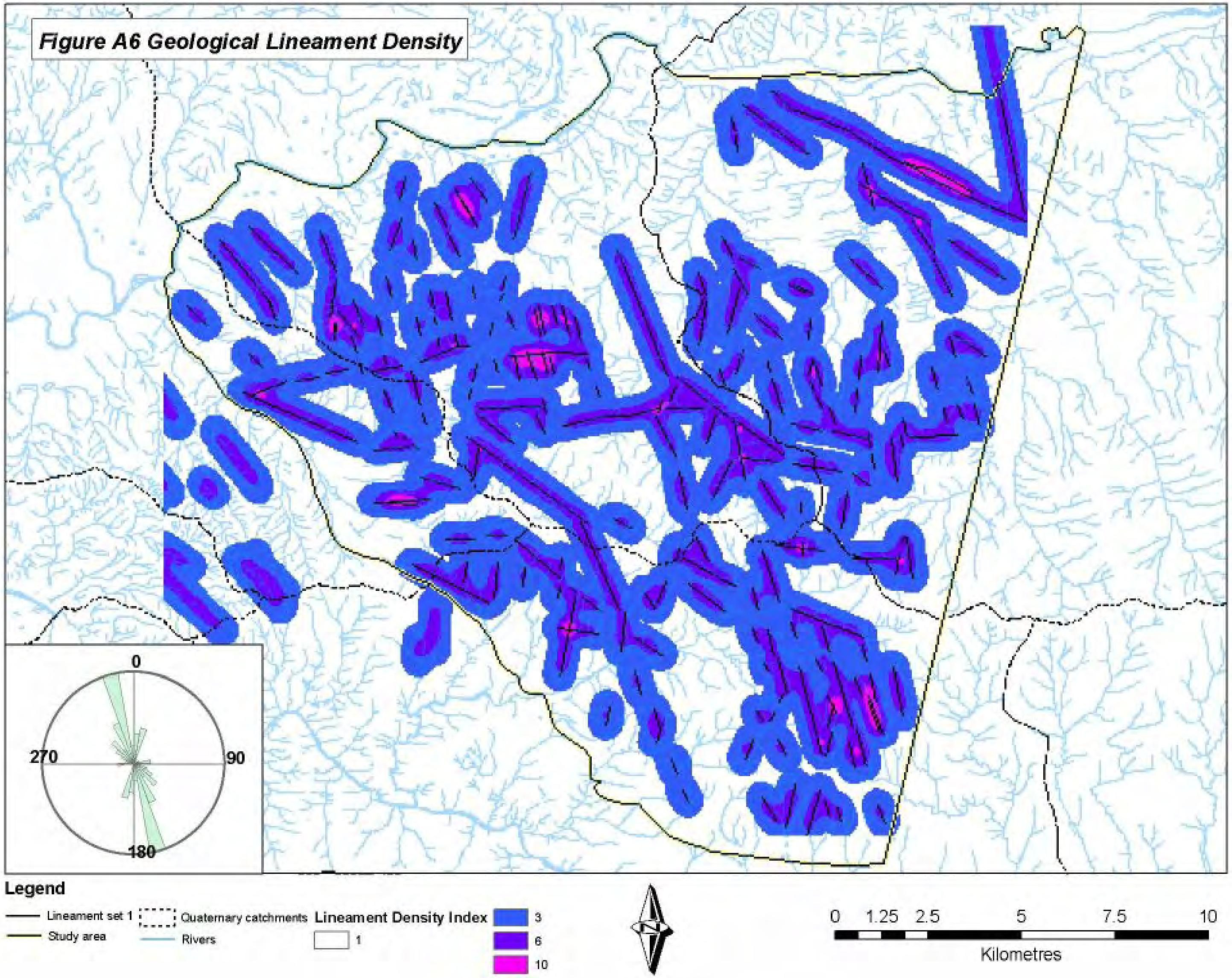


Figure A6 Geological Lineament Density
0
90
180
270
Legend
Lineament set 1
Study area
Quaternary catchments
Rivers
Lineament Density Index
1
3
6
10
0
1.25
2.5
5
7.5
10
Kilometres

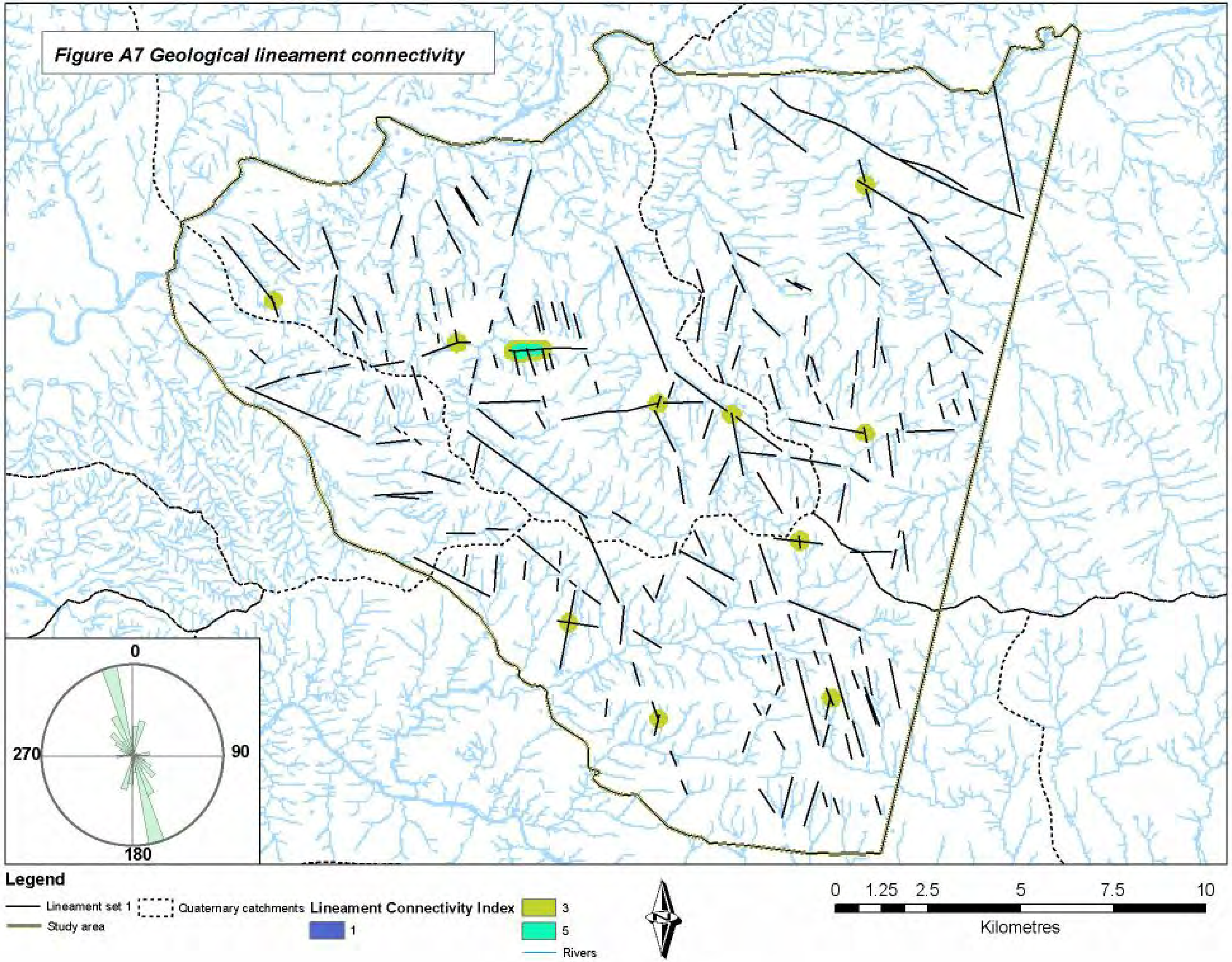


Figure A7 Geological lineament connectivity
0
90
180
270
Legend
Lineament set 1
Study area
Quaternary catchments
Lineament Connectivity Index
1
3
5
Rivers
0 1.25 2.5 5 7.5 10
Kilometres

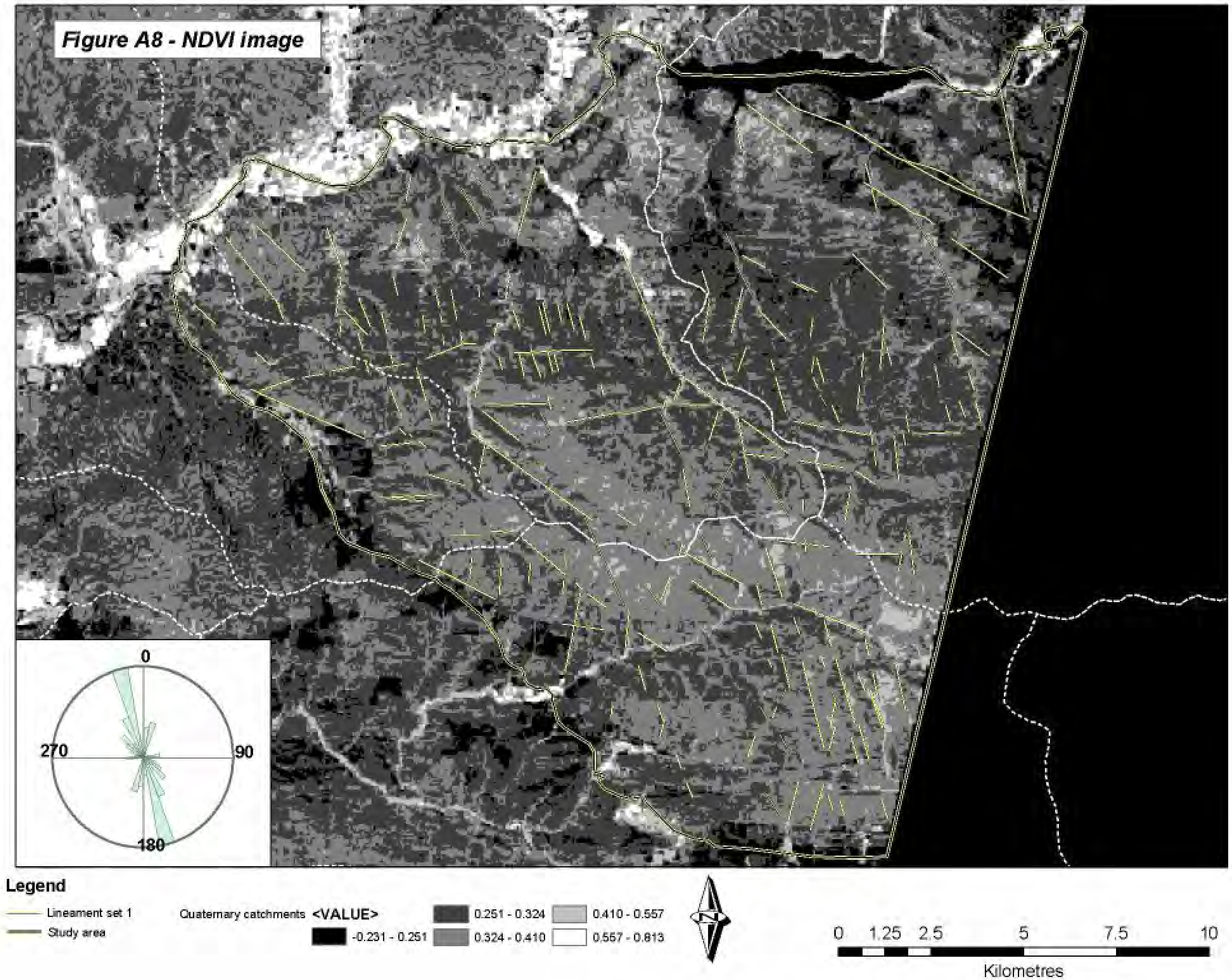


Figure A8 - NDVI image
0
90
180
270
Legend
Lineament set 1
Study area
Quaternary catchments <VALUE>
-0.231 - 0.251
0.251 - 0.324
0.324 - 0.410
0.410 - 0.557
0.557 - 0.813
0 1.25 2.5 5 7.5 10
Kilometres

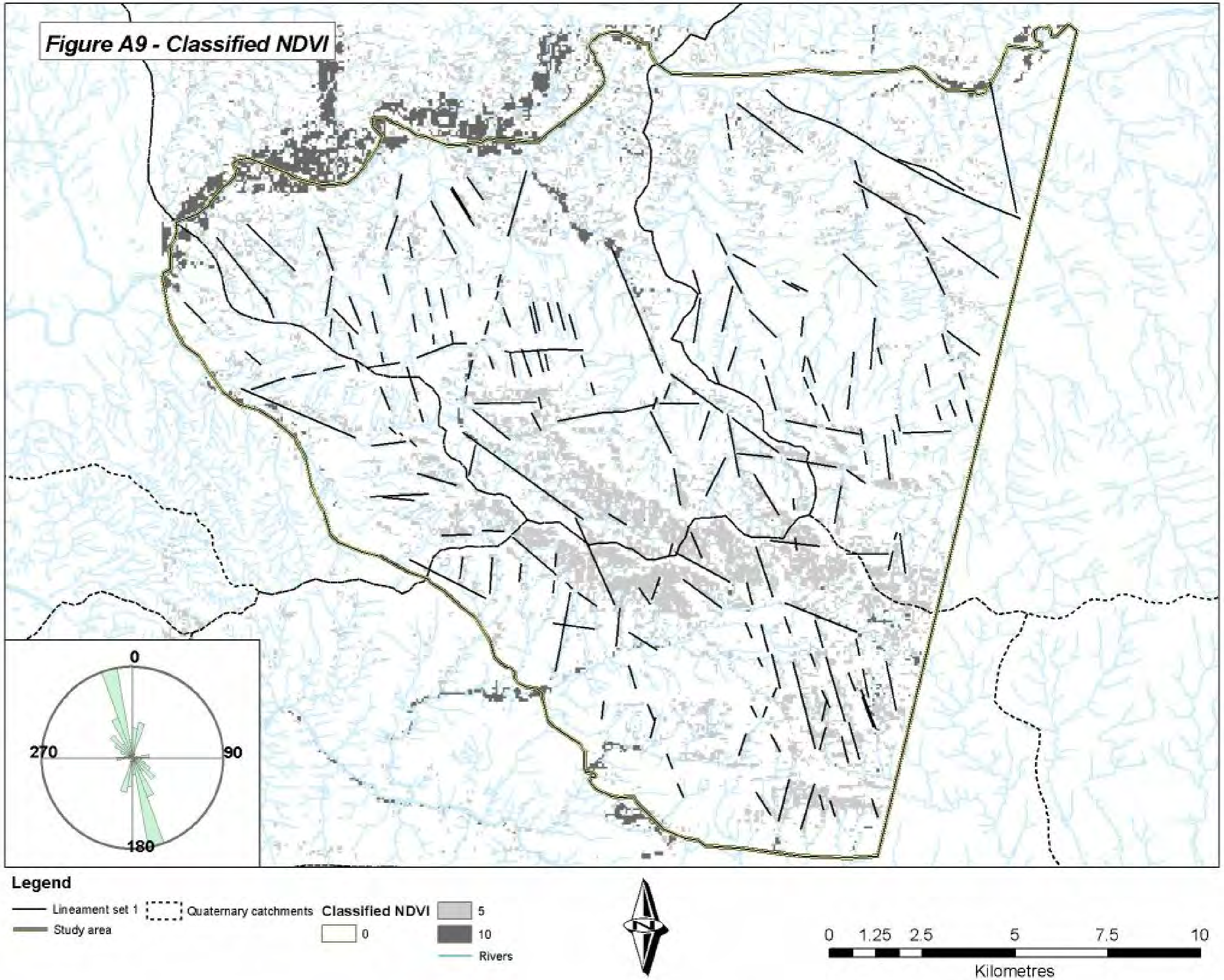


Figure A9 - Classified NDVI
0
90
180
270
Legend
Lineament set 1
Study area
Quaternary catchments
Classified NDVI
0
5
10
Rivers
N
0 1.25 2.5 5 7.5 10
Kilometres

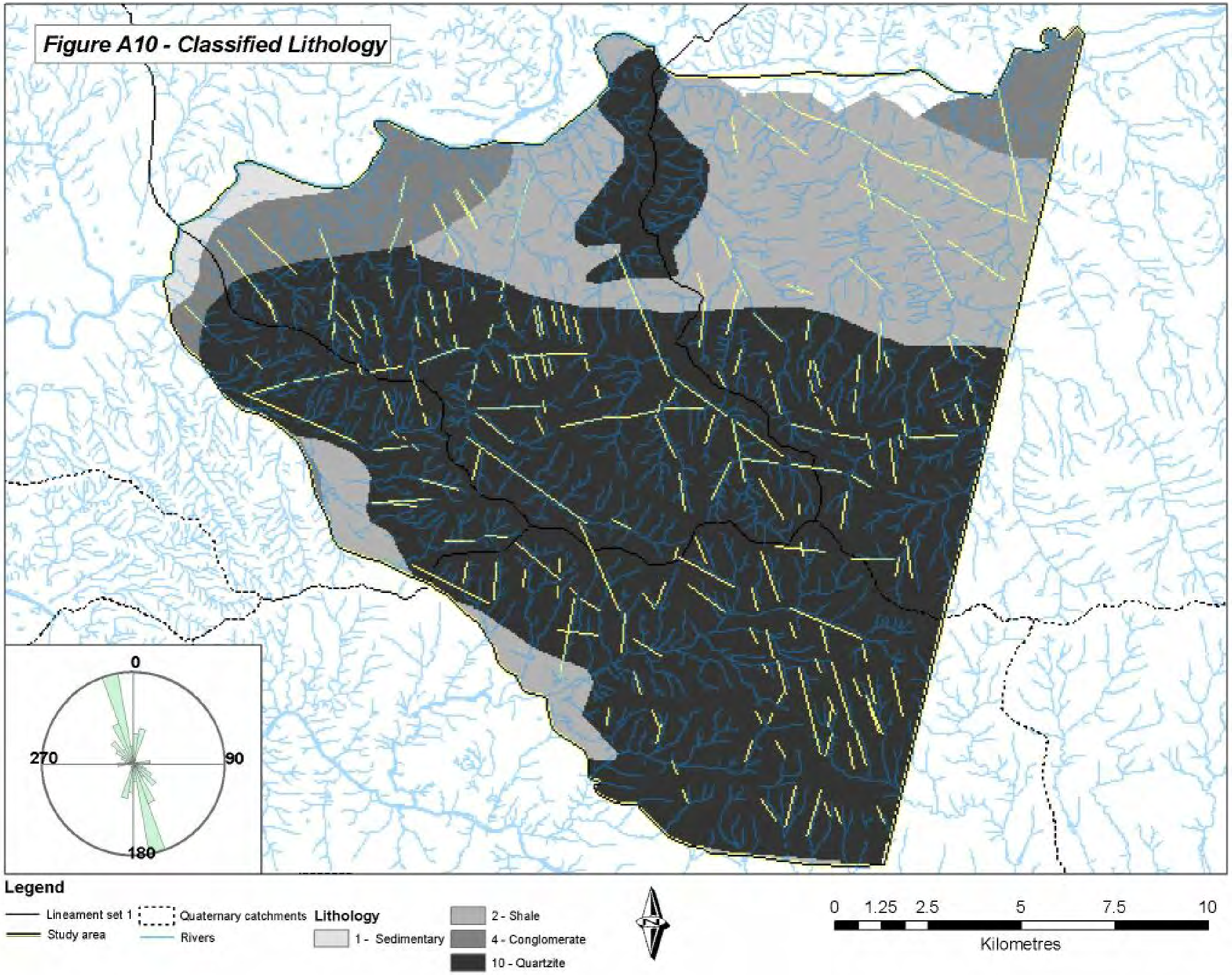


Figure A10 - Classified Lithology
0
270
90
180
Legend
Lineament set 1
Study area
Quaternary catchments
Rivers
Lithology
1 - Sedimentary
2 - Shale
4 - Conglomerate
10 - Quartzite
0 1.25 2.5 5 7.5 10
Kilometres

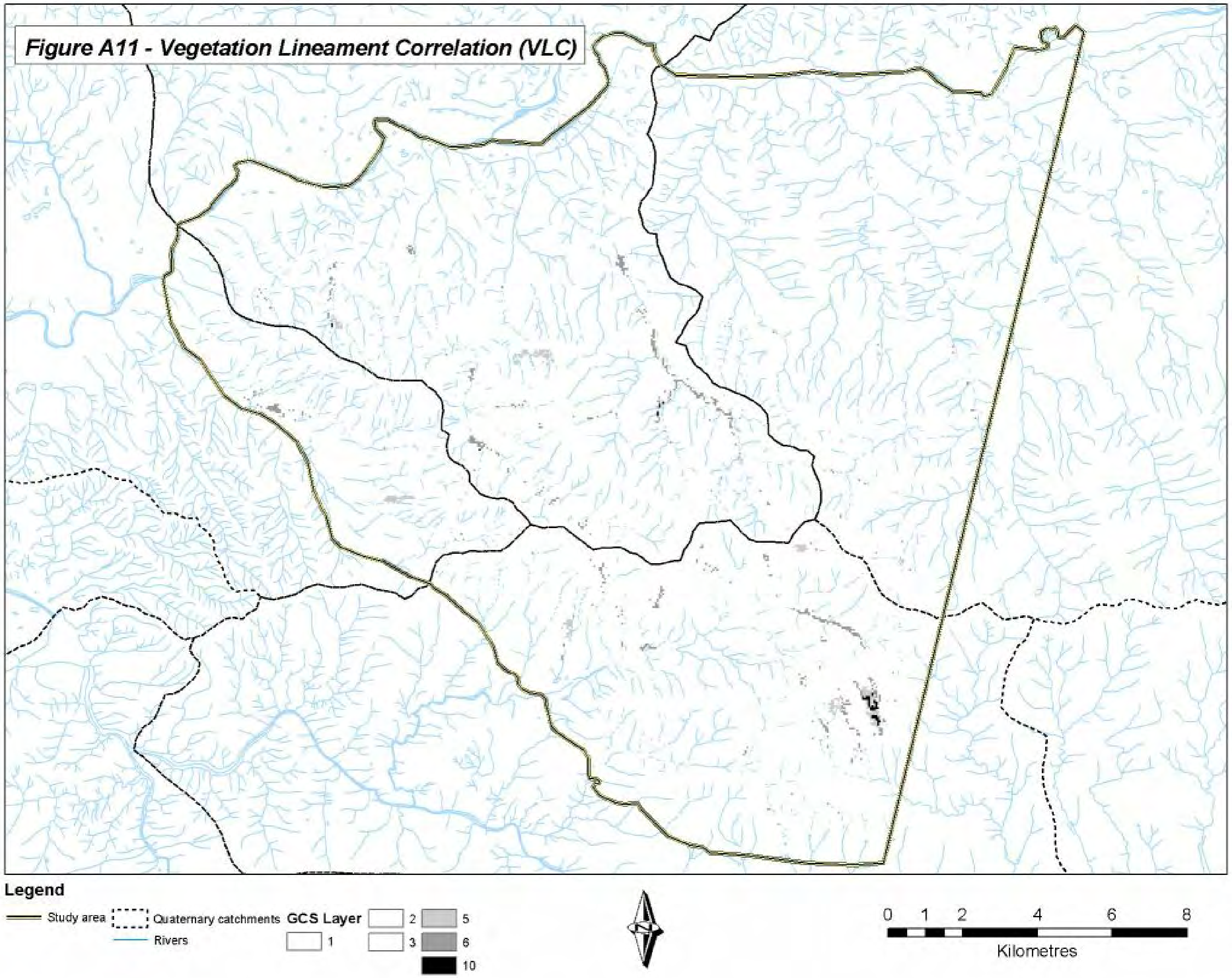


Figure A11 - Vegetation Lineament Correlation (VLC)
Legend
Study area
Quaternary catchments
Rivers
GCS Layer
1
2
3
5
6
10
0
1
2
4
6
8
Kilometres

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 Ratio 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:

Rainfall = total evaporation ± change in the soil and groundwater storage of water

The total evaporation component can be further broken down into:

Total evaporation = plant transpiration + interception + 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 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 farming in the area dates from the mid-1700s (Baynes, 1984). The sandy soils are unsuitable for cultivation so the impact of farming 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).

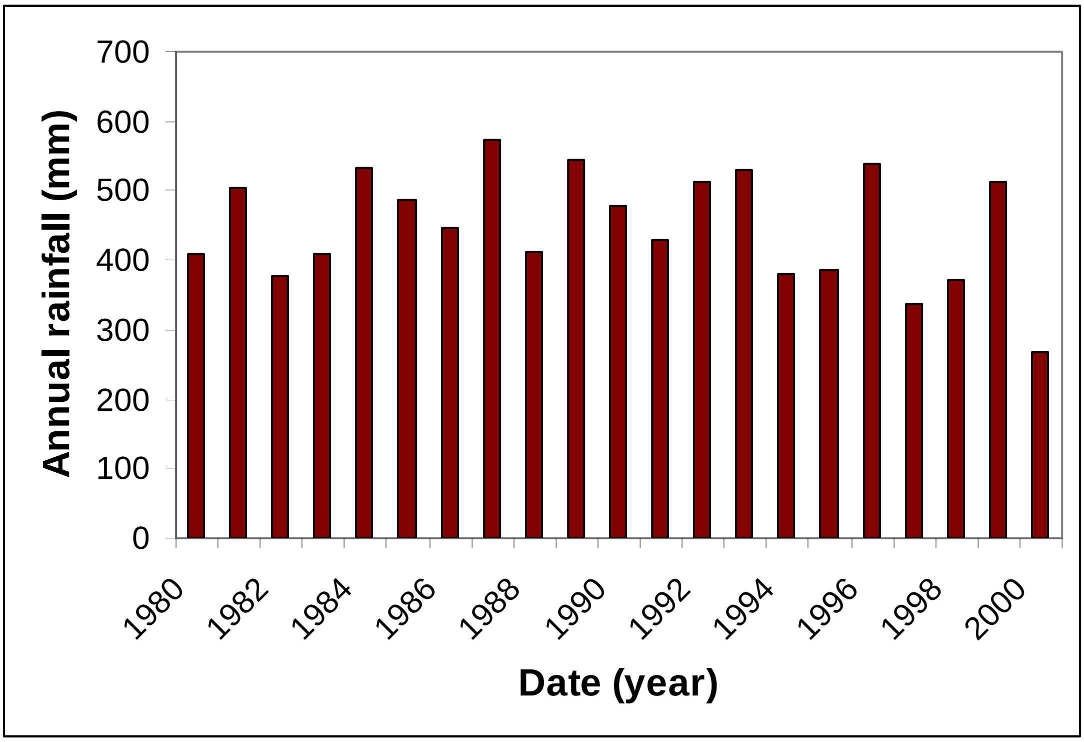


Figure B1: Annual rainfall measured at Atlantis, about 10 km northwest of the study site.

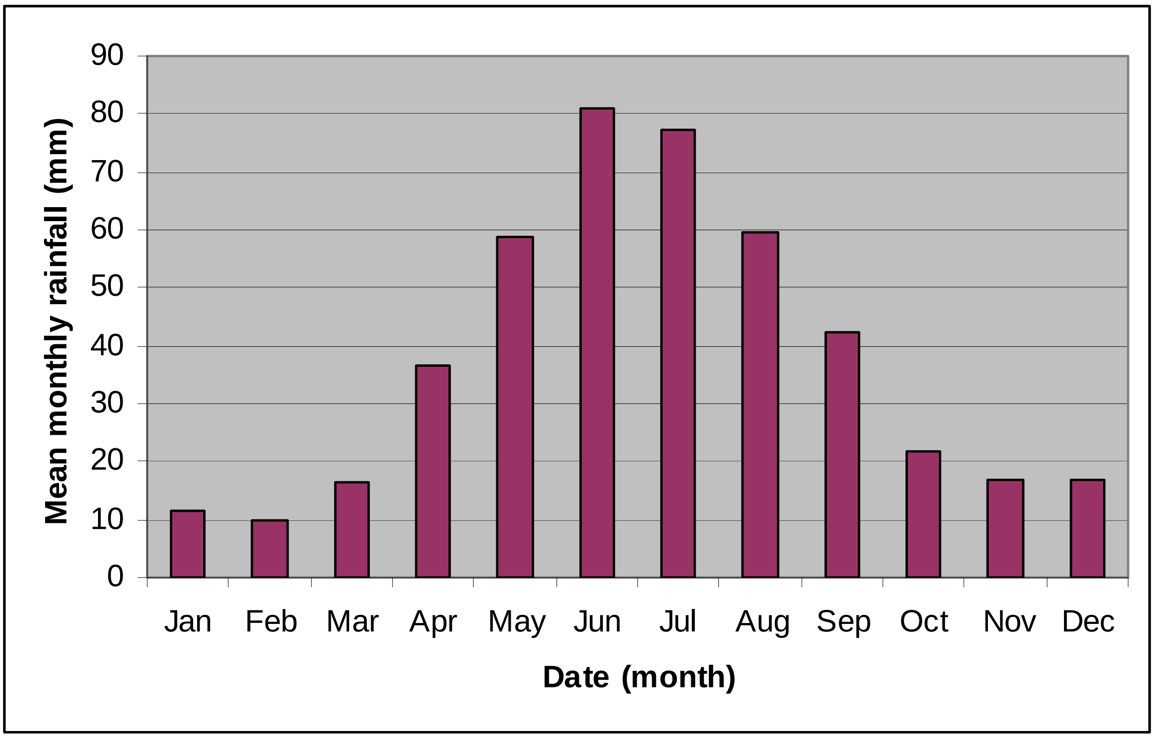


Figure B2: Mean monthly rainfall at Atlantis town for the period shown in Figure B1.

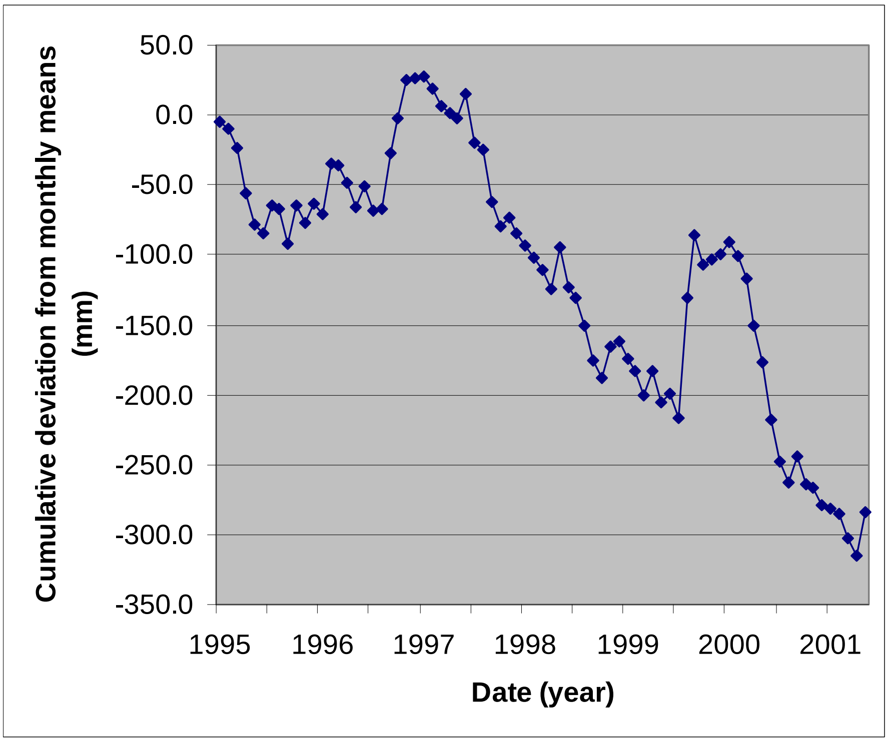


Figure B3: Cumulative deviations from the mean monthly rainfall from January 1995 to May 2001.

B3.4 Atlantis aquifer

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

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

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 *Euclea 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 *Willdenowia 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 driftsand 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 understorey 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.

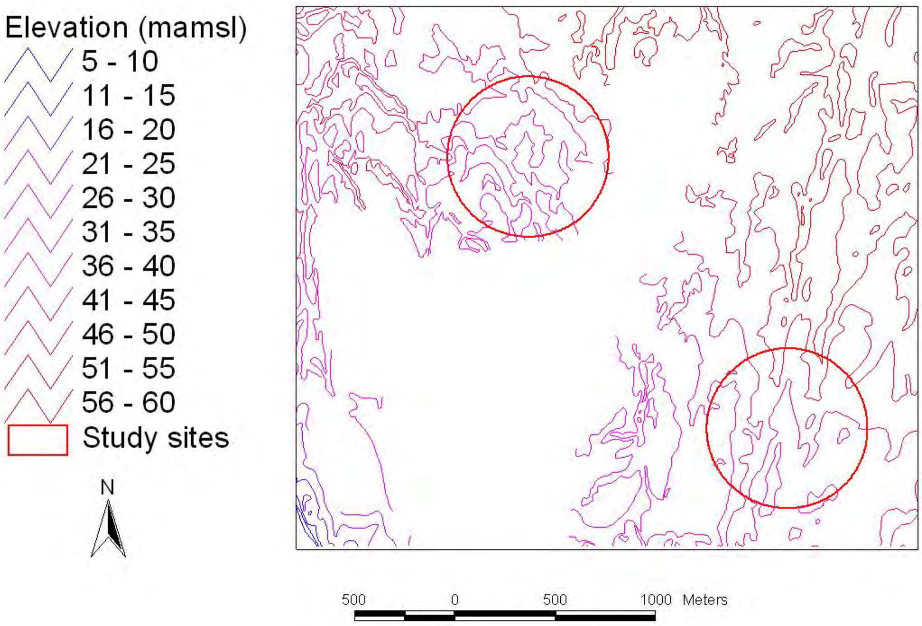


Figure B5: A map of the study sites showing the elevation and the differences in local relief.

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.

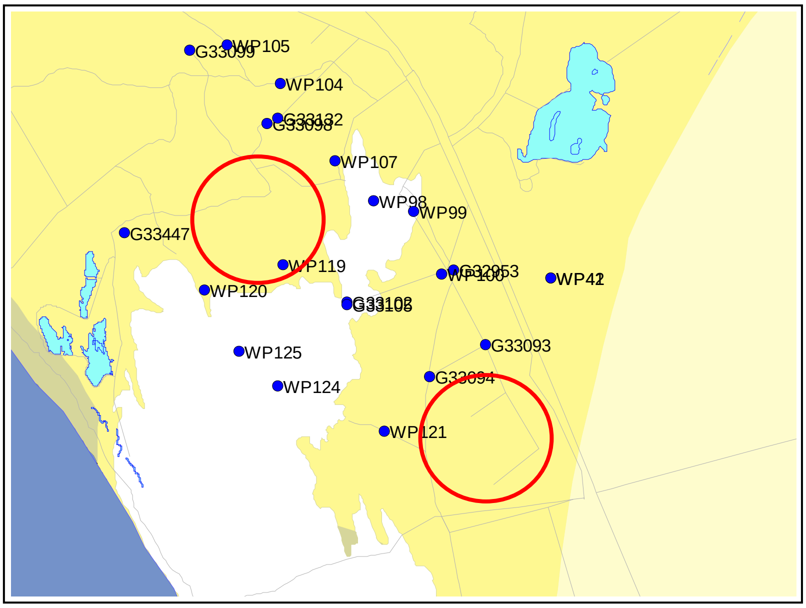
A vegetation profile of each site was compiled for the large woody shrub species to show the height, structure of the canopy and distribution of the plants. One square metre quadrats were also laid out and the leaves were removed from the shrub canopies which covered those quadrats. The leaves were put 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.



Monthly measurements:	*Two-monthly:*
WP100	WP41
WP105	WP98
WP121	WP118
G33093	WP120
G33447	WP125
WP104	G33099
WP107	G33105
G32953	WP42
G33094	WP99
	WP119
	WP124
	G33098
	G33102
	G33132

Figure B6: Water level monitoring boreholes near vegetation study sites. And the monitoring frequency.

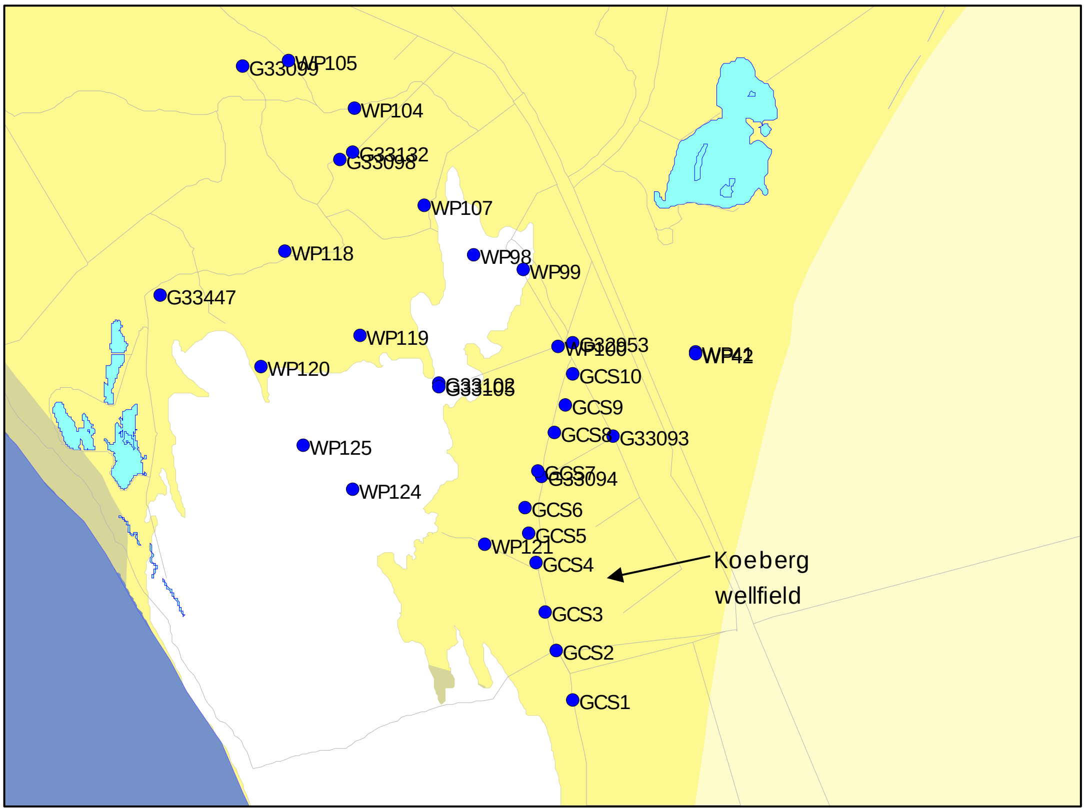


Figure B7: Location of the boreholes used to supply fresh water to the Koeberg Nuckear Power Station and its facilities.

B5.4 Measurement of evaporation

Evaporation was estimated using the Bowen Ratio technique (see Section 2) as described in 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

	2000		*2001*							
Months	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug
Strandveld										
Rooikrans										

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 raingauge 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 takes 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 (ET_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 the both the strandveld and rooikrans sites (Figure B8). This technique measures the components of the energy balance (energy fluxes) above a canopy

$$Rn - G = \lambda E + H \qquad \textbf{B.1}$$

where R_n is the net radiation, G the soil heat flux density (energy heating the soil), λE the latent heat flux density (energy driving evaporation) and H the sensible heat flux density (energy heating the air).

The latent heat flux density (λE) was calculated as

$$\lambda E = \frac{Rn - G}{\beta + 1} \qquad \textbf{B.2}$$

$$\lambda E = \frac{\rho \varepsilon K_v (e_1 - e_2)}{P(z_1 - z_2)} \qquad \textbf{B.3}$$

where β is the ratio between the sensible and latent heat flux densities, λ the latent heat of vaporization, ρ the density of the air, ε 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 δe) over a height ($z_1 - z_2$ or δz) is essential to the accurate calculation of the latent heat flux density and hence the total evaporation, ET

$$ET = \frac{\lambda E * timeconversion}{\lambda} \qquad \textbf{B.4}$$

where *timeconversion* was used to convert λE (Wm^{-2}) to ET in mm per time period. For more details on the Bowen Ratio energy balance technique see Savage *et al.,* (1997).

Figure B8: Bowen ratio energy balance system installed at a Rooikrans site (left) and a Strandveld site (right) during summer.

The large object in the foreground of the left-hand picture is a tipping-bucket rainguage.

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 (θ_v) measured with the water content reflectometers, were further converted into relative saturation values (S_e) (Van Dam *et al.,* 1997)

$$S_e = \frac{\theta_v - \theta_R}{\theta_S - \theta_R} \qquad \textbf{B.5}$$

where θ_S is the saturated soil water content and θ_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 (φ_m vs. θ_v) were determined in the laboratory from undisturbed cores collect 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

$$\Delta S = \left(S_{Initial} - S_{Final}\right) \qquad \textbf{B.6}$$

or

$$\Delta S_i = \Delta Z_i (\theta_{final} - \theta_{initial}) \qquad \textbf{B.7}$$

where $S_{initial}$ and S_{final} is the initial and final stored soil water, ΔS_i the change in the soil water content in layer *i*, ΔZ_i the thickness of the soil layer *i*, and θ_{final} and $\theta_{initial}$ 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 (θ_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 (θ_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

	Soil physical characteristics						
Site	*Depth (m)*	*Clay %*	*Silt %*	*Fine sand %*	*Medium sand %*	*Coarse Sand %*	*Stone %*
Strandveld	0.1	1.5	1	29.1	68	0.7	0
Strandveld	0.5	1.8	1	19.8	73.8	4	0
Strandveld	0.9	1.3	0	25.8	70.5	2	0
Rooikrans	0.1	1.2	0	23.6	71.5	3.4	0
Rooikrans	0.5	0.9	0	19.9	73.4	5.6	0
Rooikrans	0.9	1.2	0	21.6	63.4	13.7	0

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

Study sites	*Depth (m)*	*Mualen-Van Genuchten parameters*				
		θ_R cm^3cm^{-3}	θ_S cm^3cm^{-3}	α	*n*	*m*
Strandveld	-0.1	0.0344	0.3578	0.0817	1.6043	0.3767
	-0.5	0.0539	0.3041	0.0221	5.6231	0.8222
	-0.9	0.0586	0.3716	0.0207	7.0946	0.8590
Rooikrans	-0.1	0.0603	0.4357	0.0263	8.0412	0.8756
	-0.5	0.0062	0.3543	0.0202	10.8288	0.9077
	-0.9	0.0417	0.1465	0.0094	5.0540	0.8021

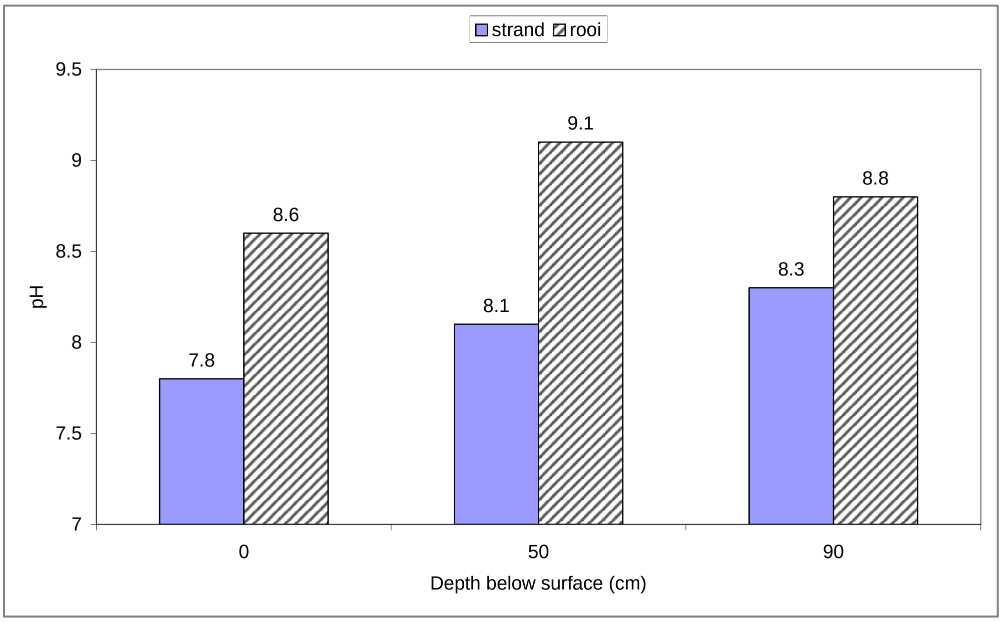


Figure B9: pH (KCl)[6] at the strandveld and rooikrans sites

[6] *The pH of the soil indicates the degree of acidity of the soil to the suspension medium.*

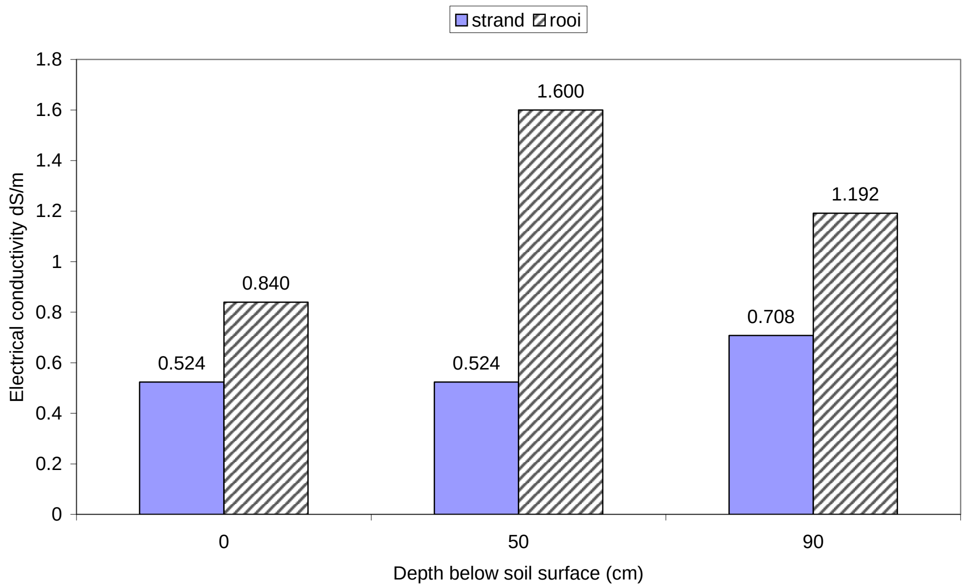


Figure B10: Electrical conductivity[7] at the strandveld and rooikrans sites

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 understorey 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 (m^2) 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.

[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 m^2 sample plots

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

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 vists 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.

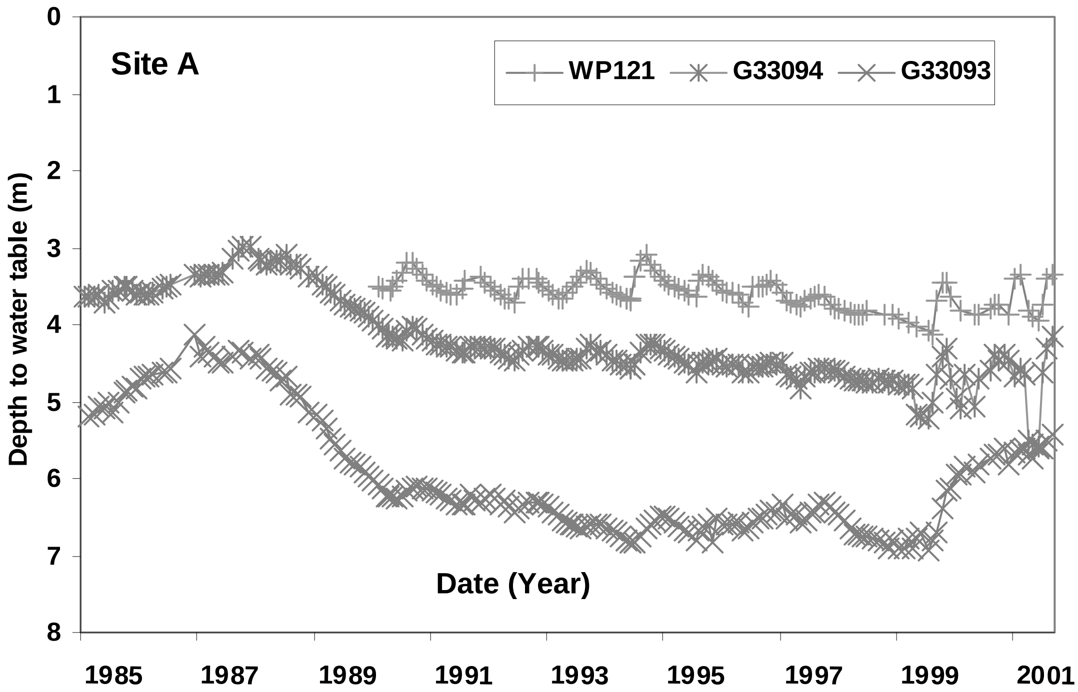


Figure B11: Depths to the water table measured at monitoring boreholes located close to site A, the strandveld site.

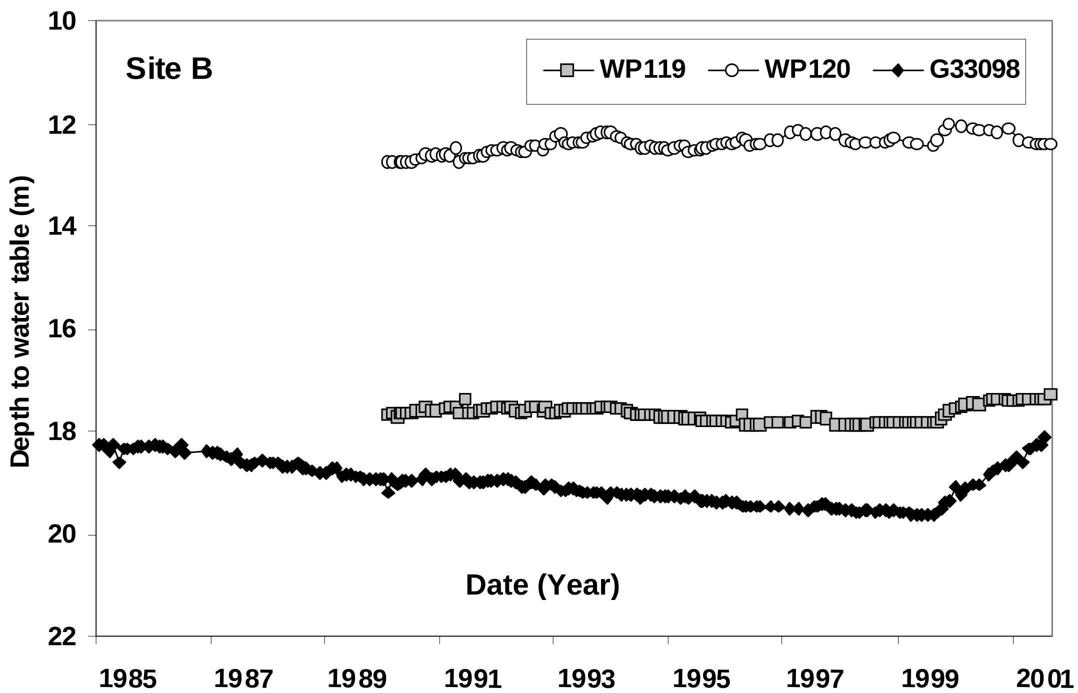


Figure B12: Depths to the water table measured at monitoring boreholes located close to site B, the Rooikrans site.

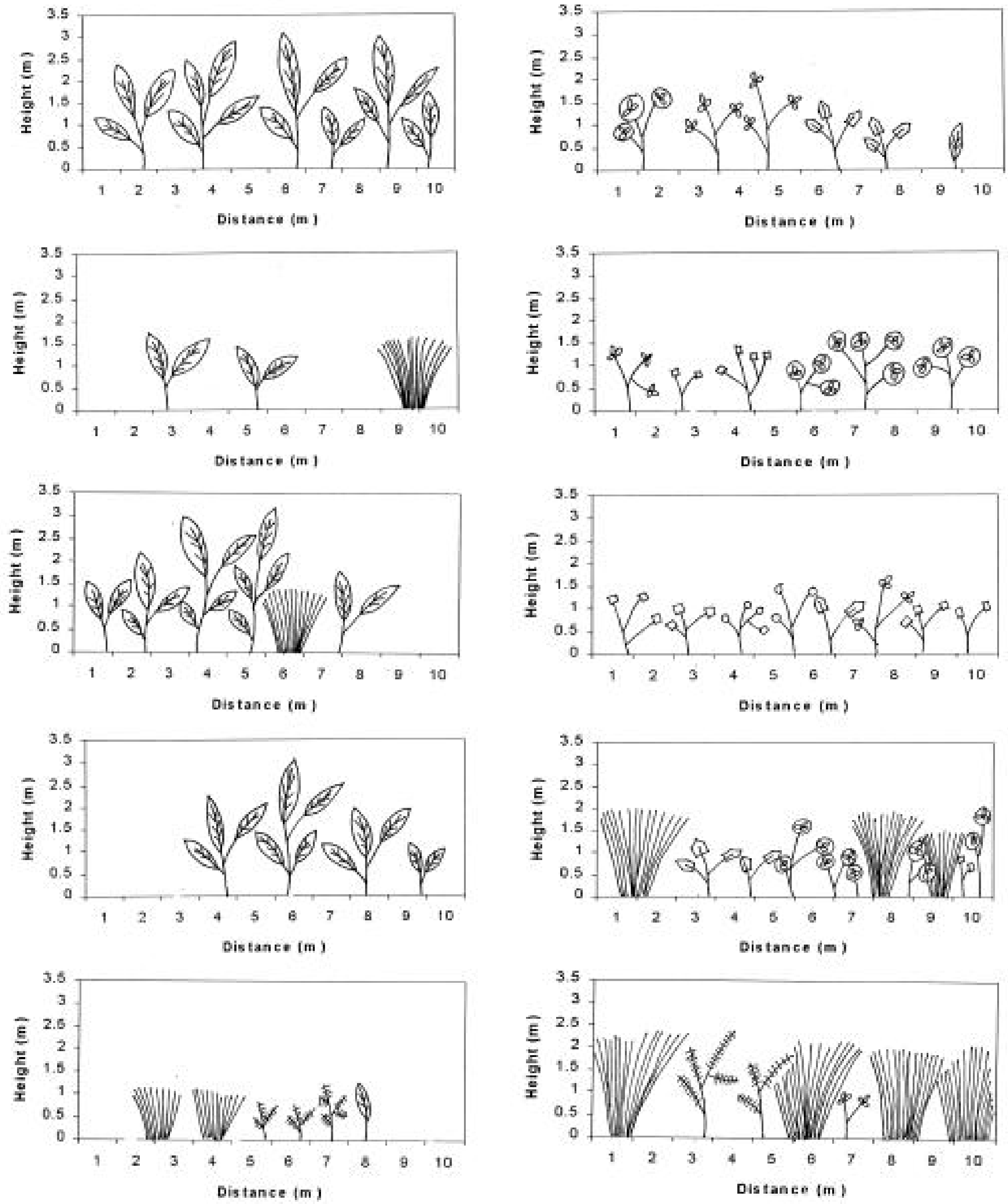


Figure B13: Selected stand structure profiles from the April sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15.

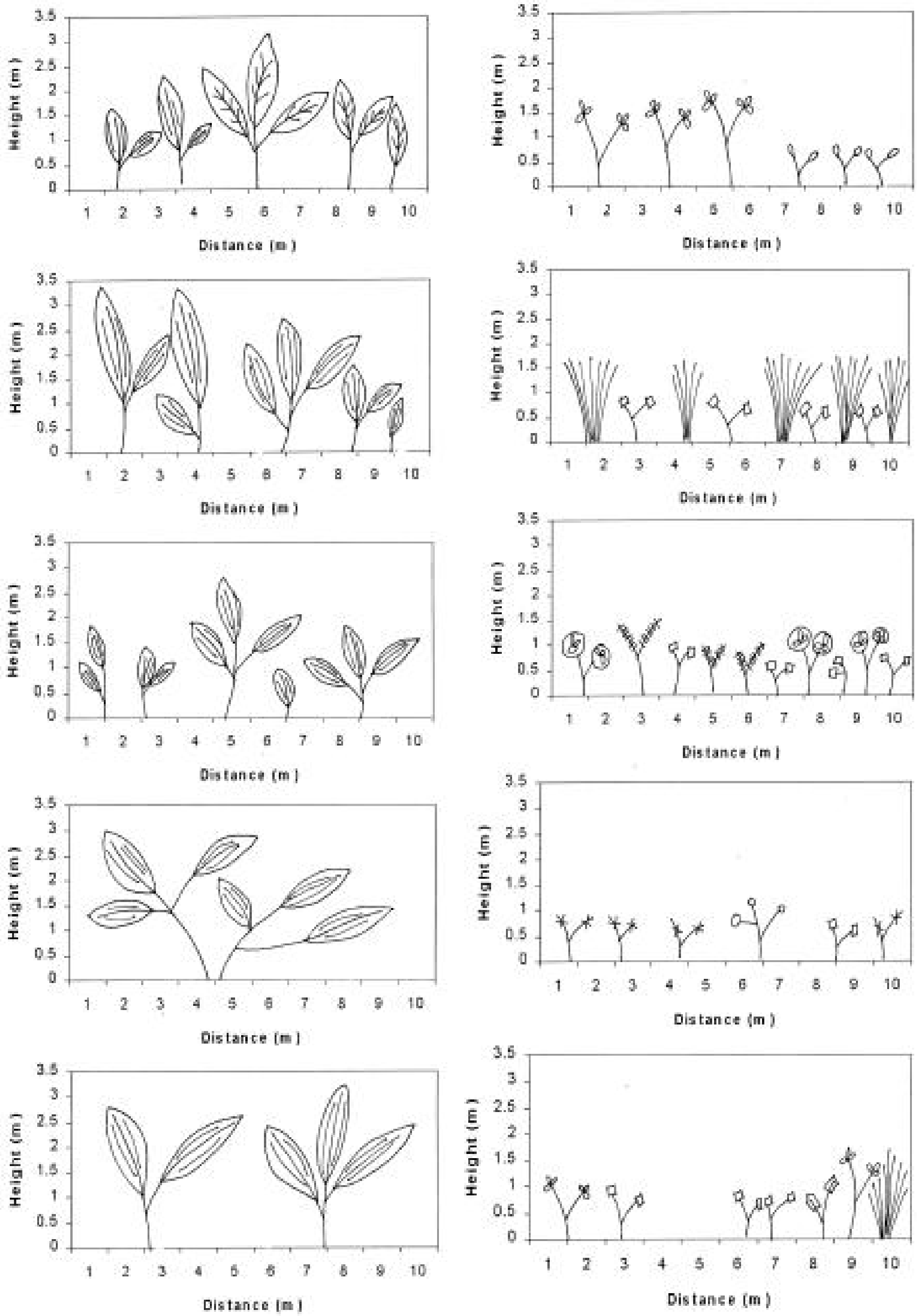


Figure B14: Selected stand structure profiles from the August sampling period. Rooikrans site on the left and Dune Thicket (Strandveld) on the right. For the key see Figure B15.

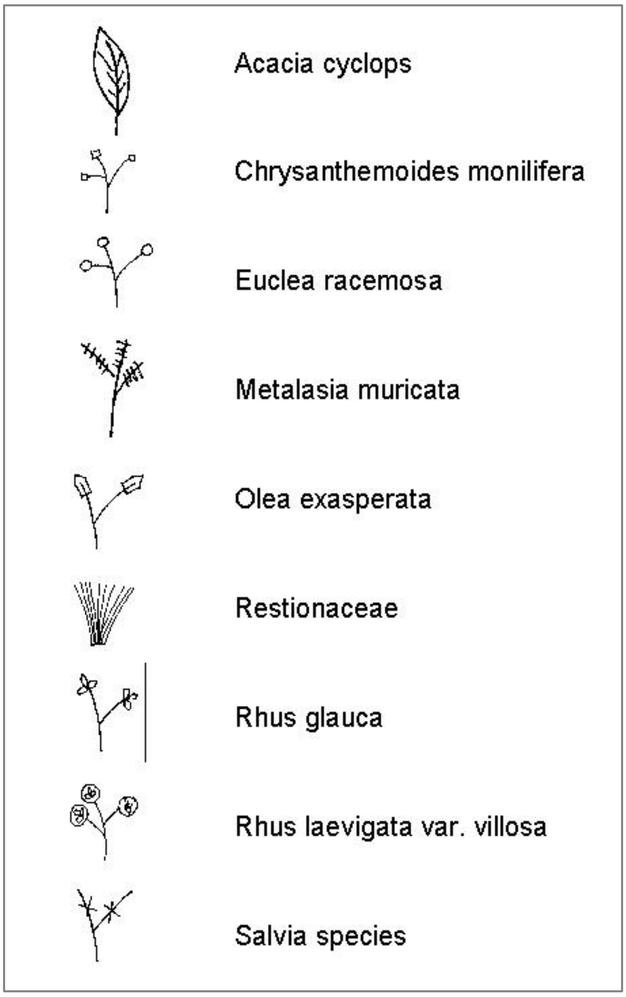


Figure B15: Key to the plant species in the structure profiles

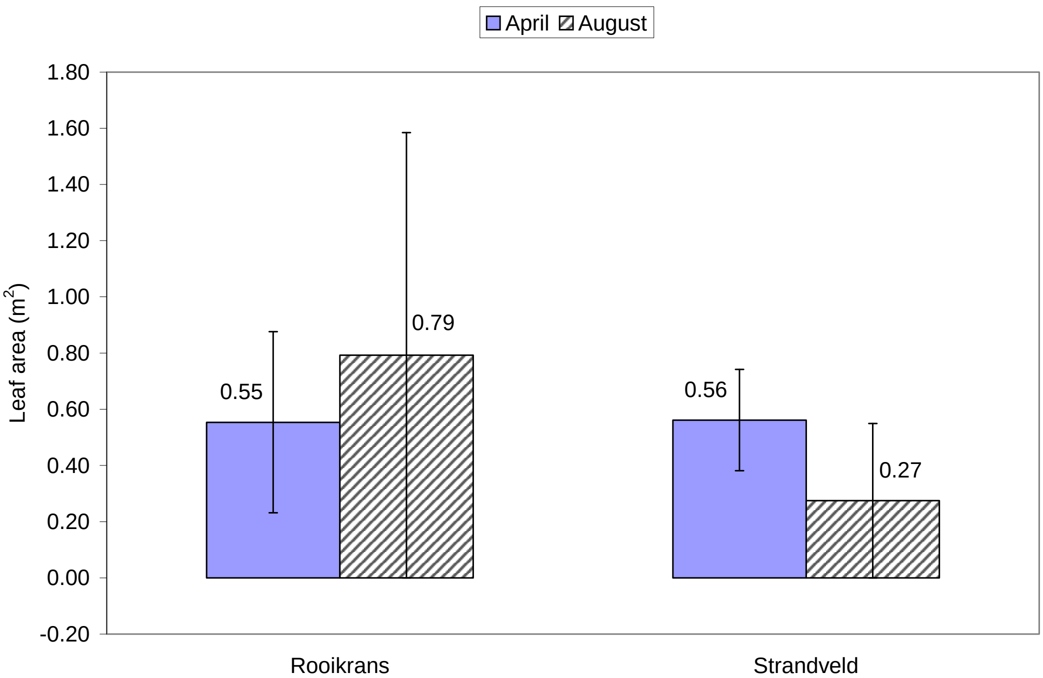


Figure B16: Average leaf area indexes (m^2/m^2) at the dune thicket (Strandveld) and Rooikrans sites during autumn and winter 2001.

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.

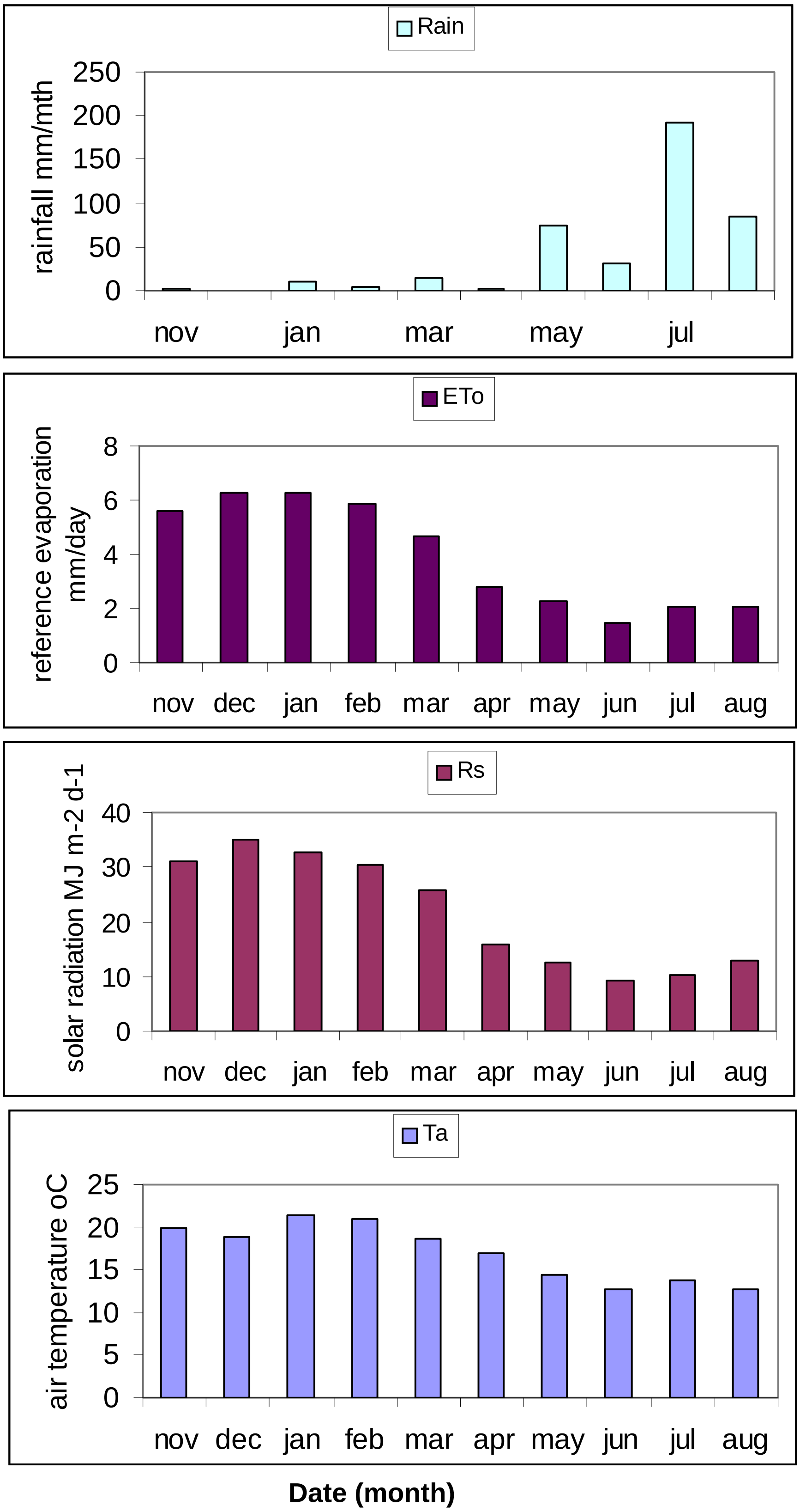


Figure B17: Summary of the monthly total rainfall (rain), monthly average reference evaporation (ET_o), monthly total solar radiation (R_s), and the monthly mean air temperature (T_a) measured from 30 November 2001 to 1 September 2001.

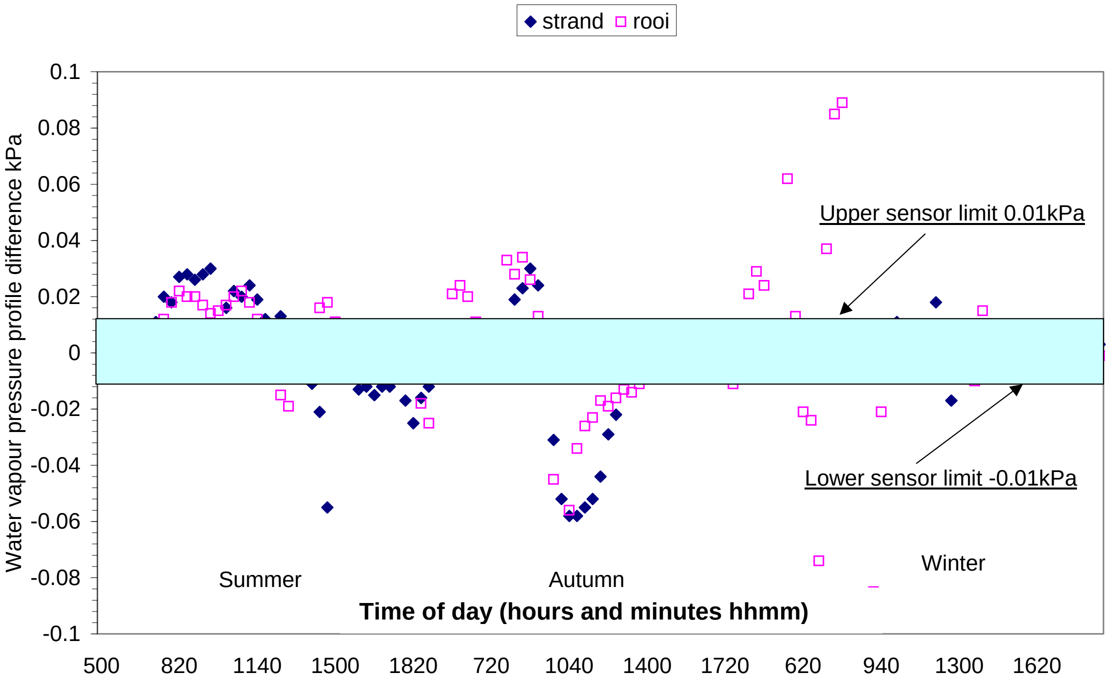


Figure B18: Water vapour pressure difference at the strandveld and rooikrans sites during three selected days representing summer, autumn and winter conditions.

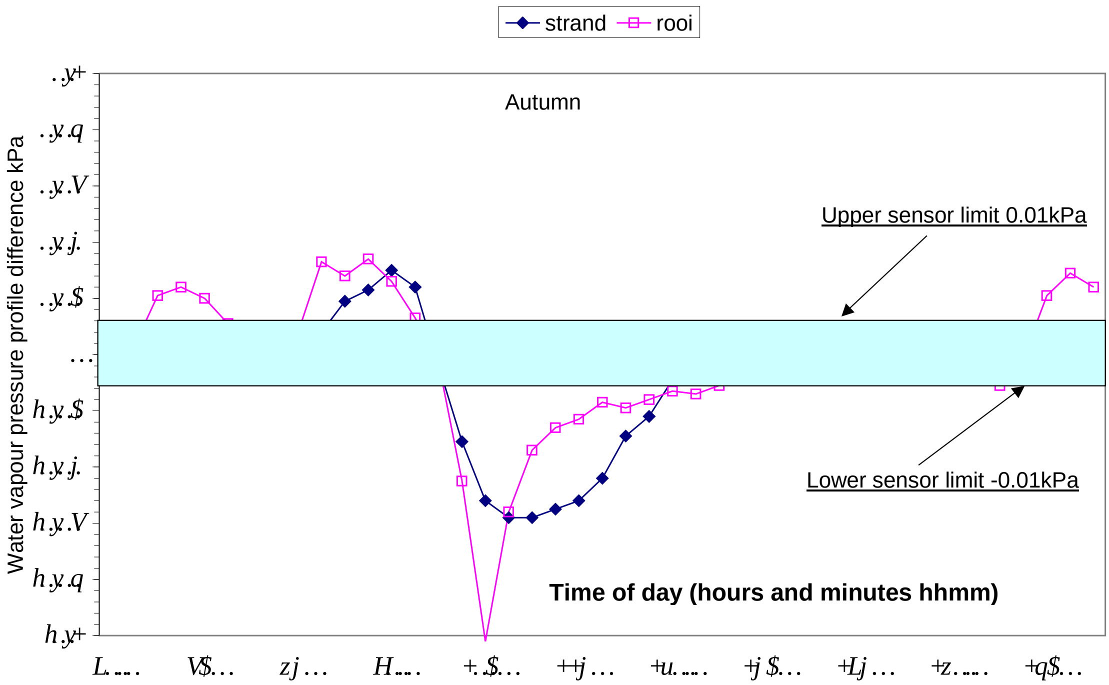


Figure B19: Water vapour pressure difference at the strandveld and rooikrans sites during autumn

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 λE) 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) λE above a strandveld and rooikrans canopy are shown in Figure B19. Most of the λE data were rejected as a result of sensor problems. During summer and winter, the rooikrans λE values are slightly lower than those for strandveld, and the potential rooikrans λE values are slightly smaller than those for strandveld. However, during autumn, the measured Bowen Ratio (bet) and potential (eqet) λE values at the rooikrans site exceeded those at the strandveld site. The total daily potential λE (eqet) at the strandveld site (14.6, 7.0 and 3.9 $MJm^{-2}day^{-1}$ during summer, autumn and winter respectively) differed slightly from that at the rooikrans site, being 13.6, 8.2 and 3.7 $MJm^{-2}day^{-1}$ 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 λE 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 λEs 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.

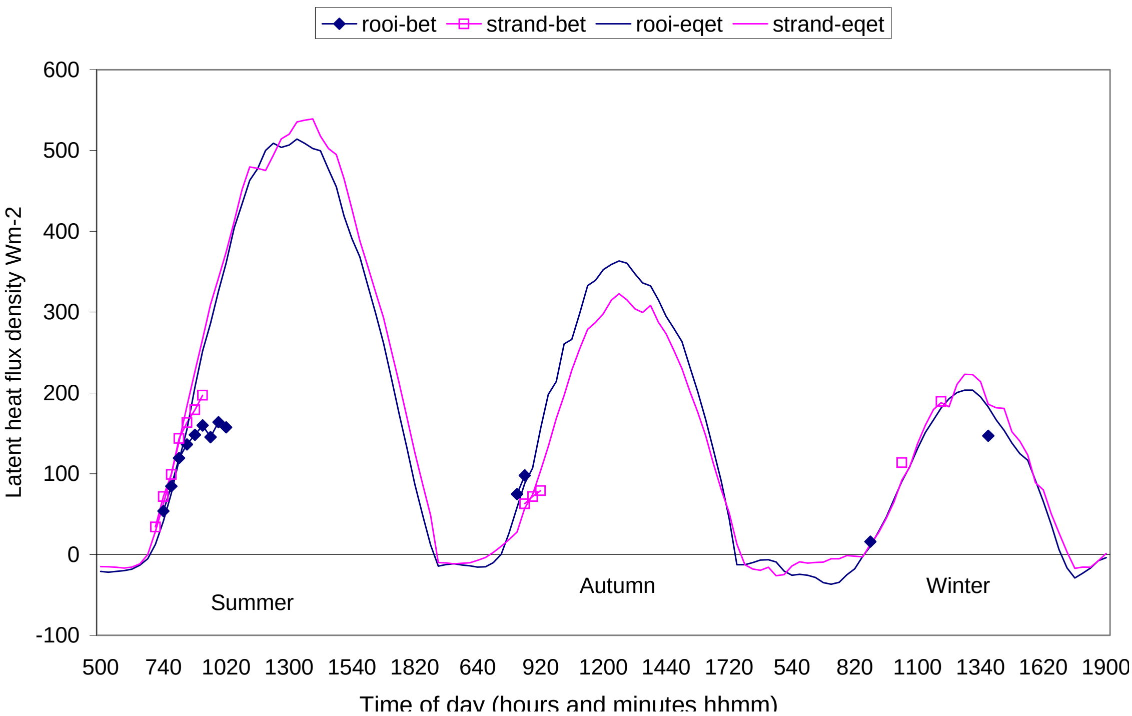


Figure B20: Latent heat flux densities at the strandveld and rooikrans sites for three selected days representing summer, autumn and winter conditions.

Note: bet refers to the latent heat flux density for 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%.

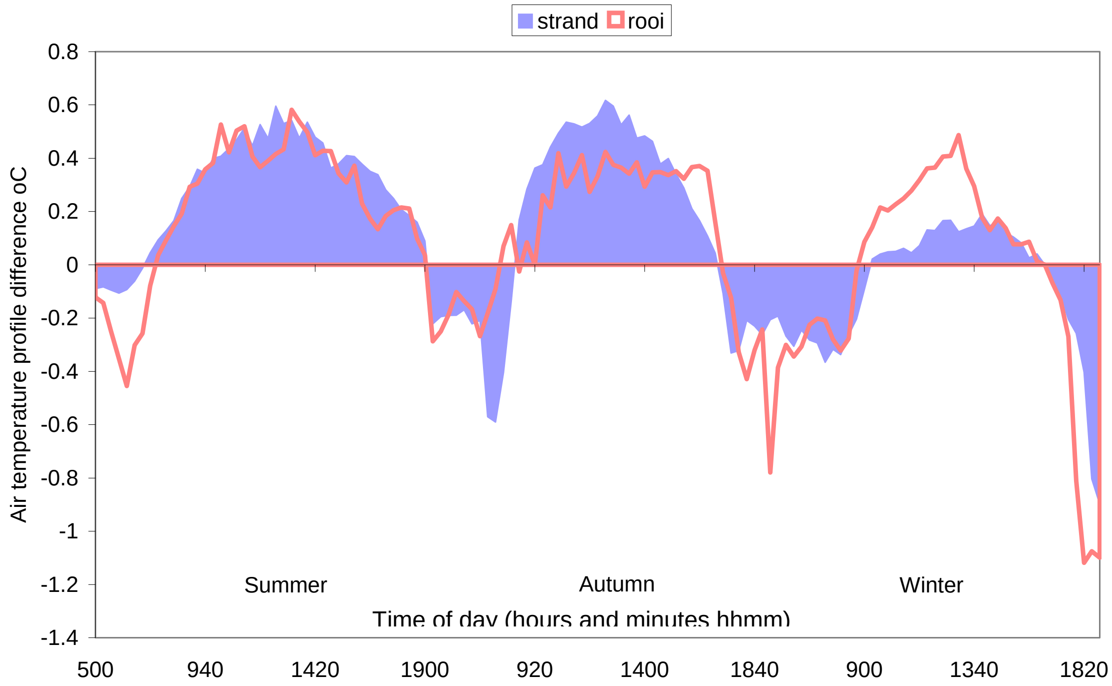


Figure B21: Air temperature profile differences at the strandveld and rooikrans sites for three sample days during summer, autumn and winter

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 (R_n-G) can be partitioned between the energy driving evaporation (λE) 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 MJm^{-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.

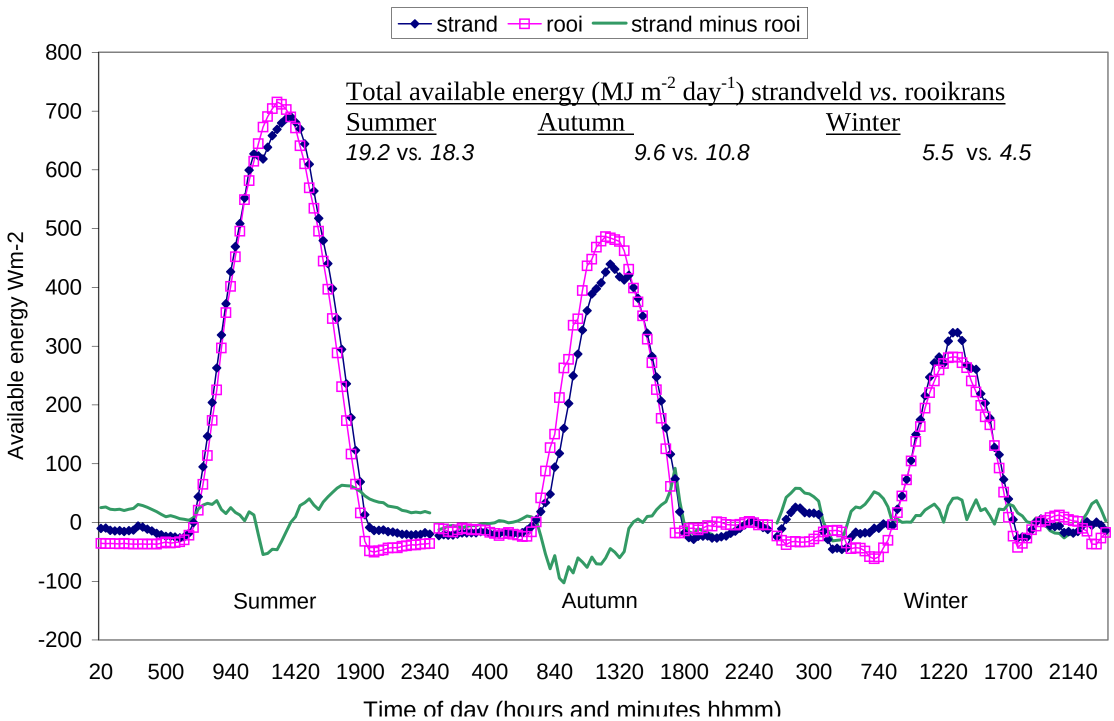


Figure B22: Available energy at the strandveld and rooikrans sites, and the difference in the available energy between these sites for three sample days during summer, autumn and winter

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 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 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.

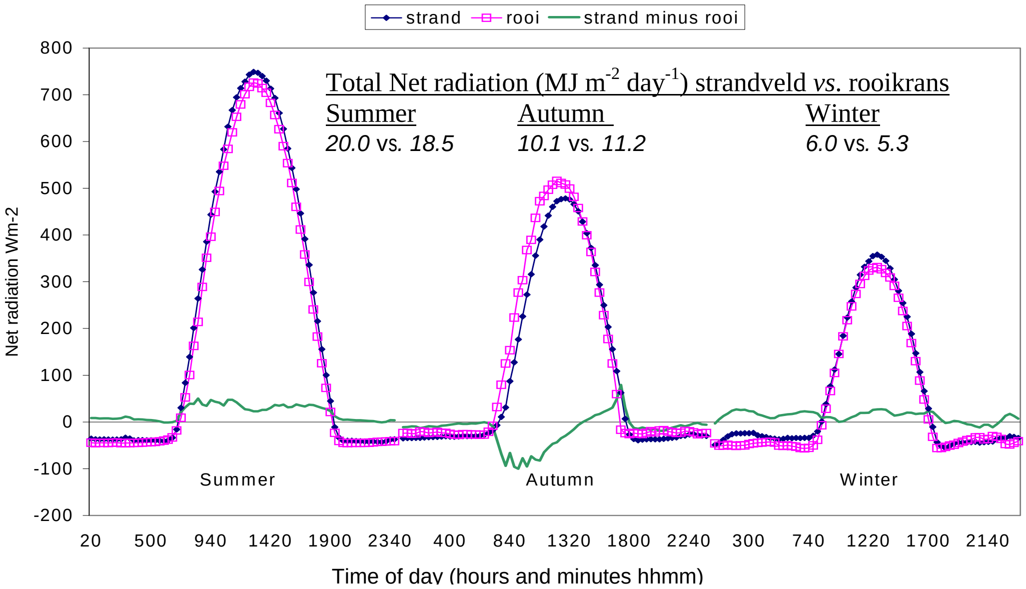


Figure B23: Net radiation at the strandveld and rooikrans sites, and the difference in the net radiation between these sites for three sample days during summer, autumn and winter

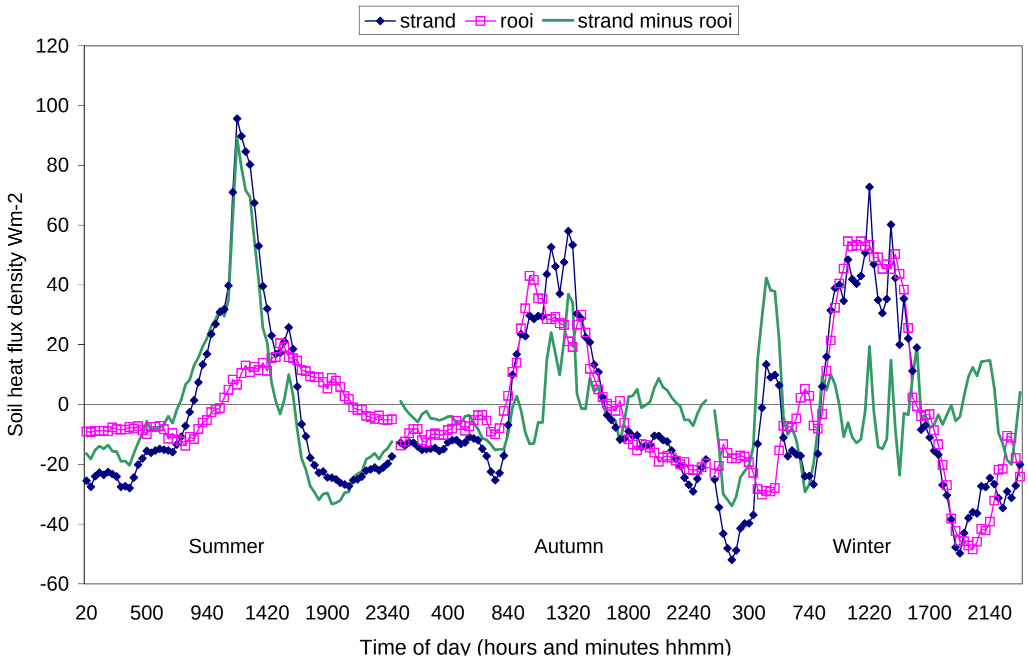


Figure B24: Soil heat flux density at the strandveld and rooikrans sites, and the difference in the soil heat flux density between these sites for three sample days during summer, autumn and winter

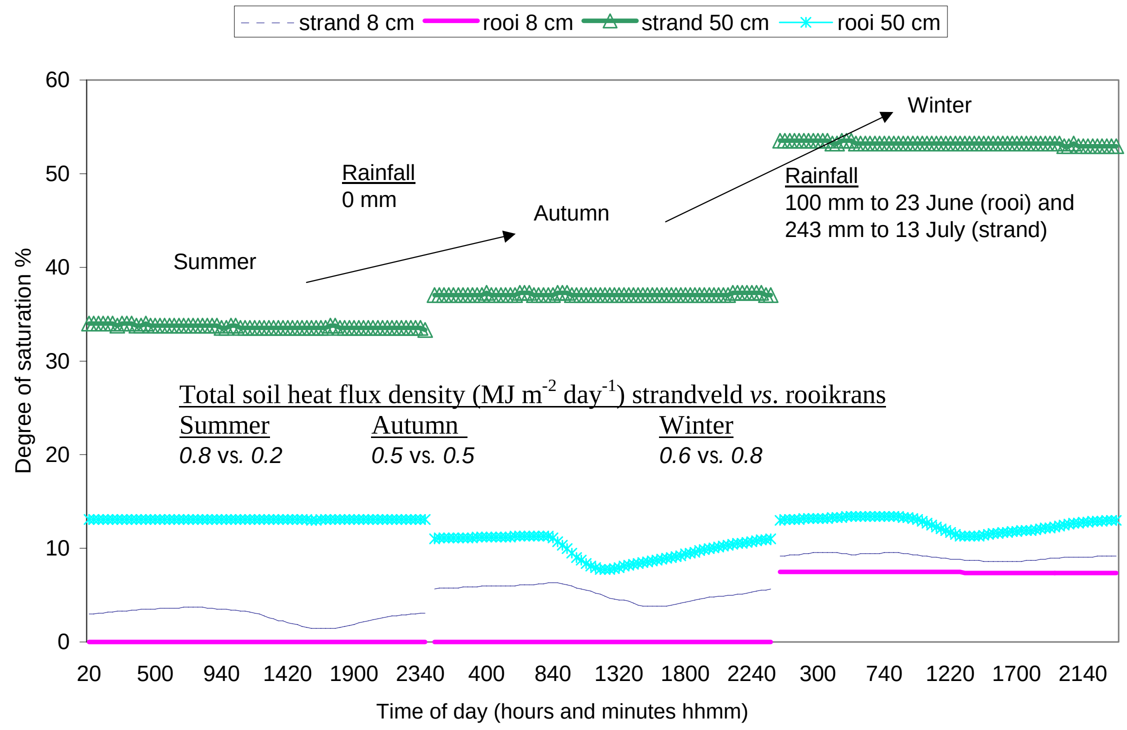


Figure B25: Effective degree of saturation at the strandveld and rooikrans sites at 80 mm and 500 mm below the soil surface for three sample days during summer, autumn and winter

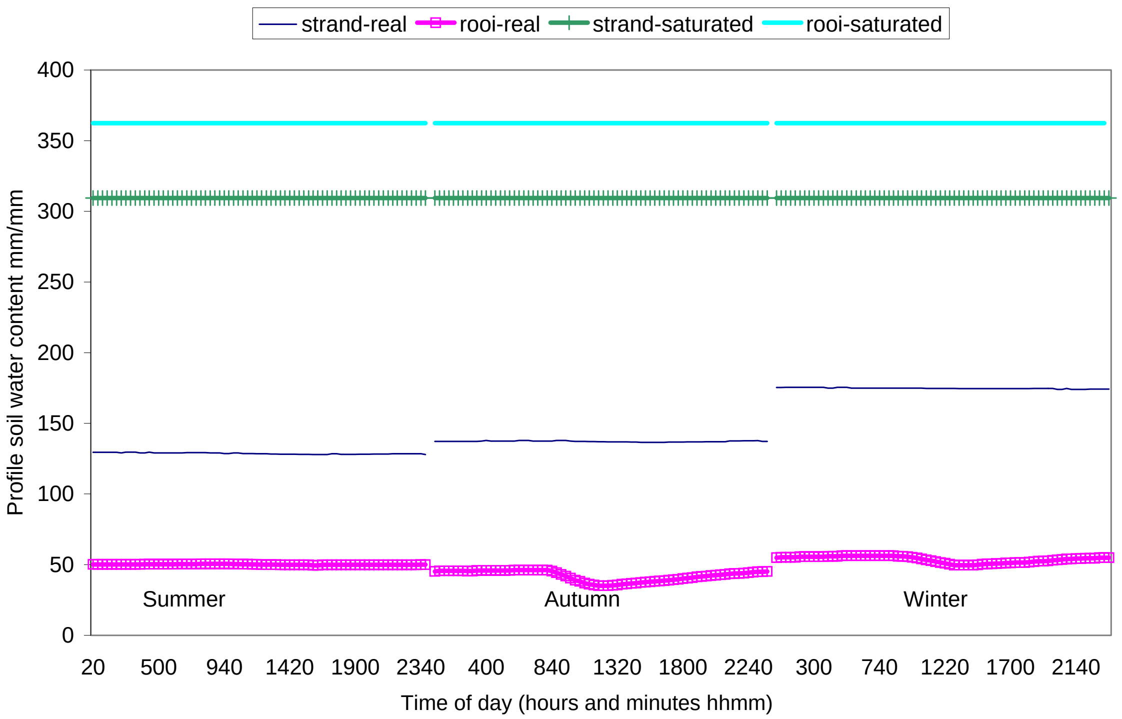


Figure B26: Profile soil water content at the strandveld and rooikrans sites over a depth of 1000 mm for three sample days during summer, autumn and winter

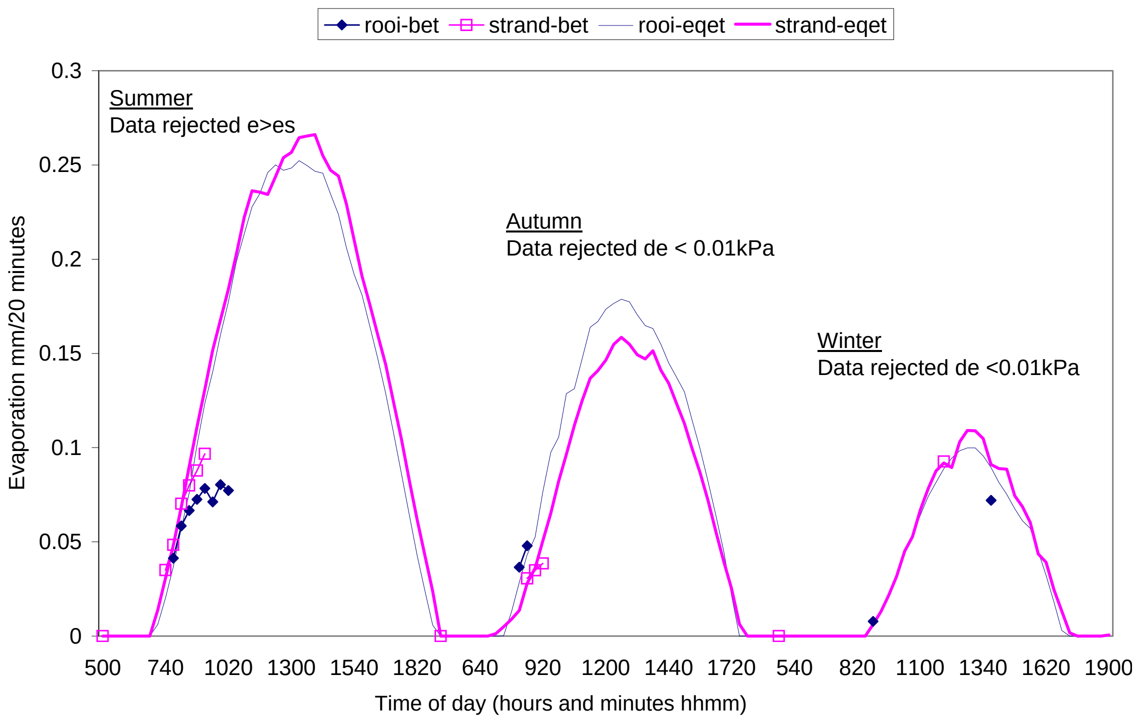


Figure B27: Percentage of the strandveld and rooikrans profiles (100 cm) filled to its capacity on three sample days during summer, autumn and winter

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 0.01kPa, 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

Component	*Summer*	*Autumn*	*Winter*
R_n-G	Strand >Rooi (7%)	Strand < Rooi (10%)	Strand > Rooi (11%)
dT	Strand > Rooi (75%)	Strand > Rooi (75%)	Strand < Rooi (77%)
Comment	More available energy at the strandveld site	More available energy at rooikrans dT small at rooikrans, therefore most of energy possibly to Latent heat flux density at Rooikrans Evaporation possibly higher at rooikrans that strandveld	More available energy at 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}).

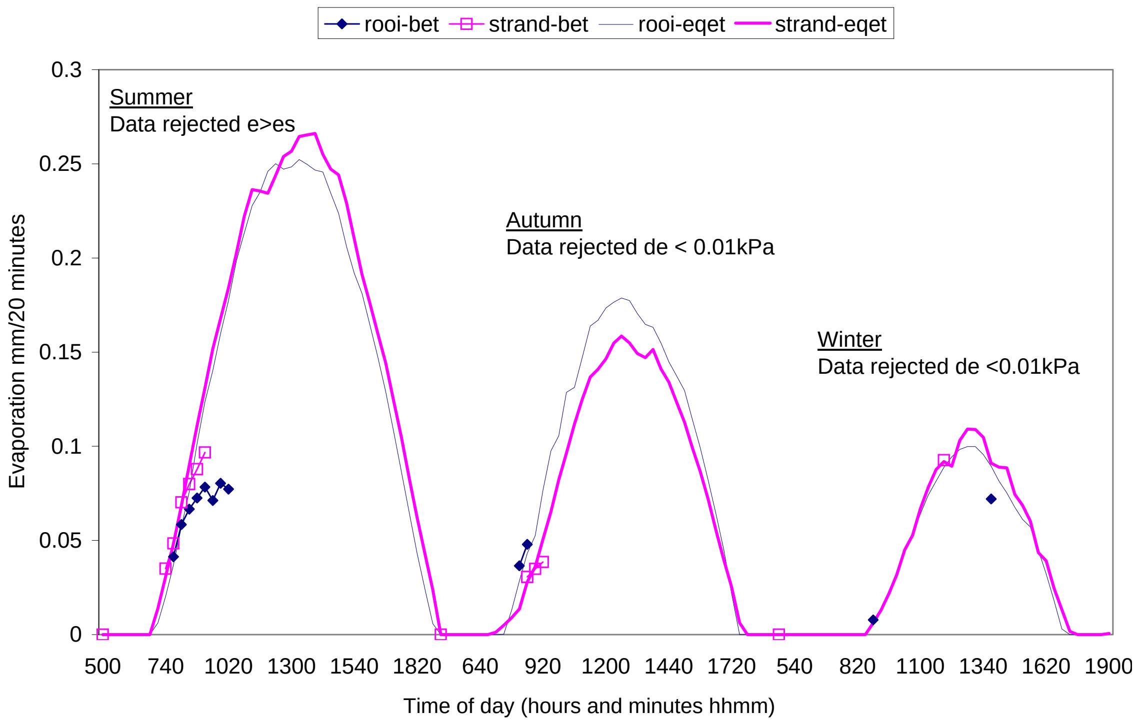


Figure B28: Bowen ratio evaporation (bet) and equilibrium evaporation (eqet) at the strandveld and rooikrans sites for three sample days during summer, autumn and winter ays

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 emphasises 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 standveld 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.

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ADDENDUM 1.

A LIST OF THE DOMINANT SPECIES RECORDED DURING THE VEGETATION SURVEY.

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

REFERENCES

Acocks, JPH 1953. Veld types of South Africa with map, scale 1: 1 500 000. Botanical Survey of South Africa Memoir No. 28, Department of Agriculture, Pretoria.

Acocks, JPH 1975. Veld Types of South Africa (2nd ed.). Memoirs of the Botanical Survey of South Africa No. 40, National Botanical Institute, Pretoria.

Acocks, JPH 1976. Riverine vegetation of the semi-arid and arid regions of South Africa. Journal of the South African Biological Society 17: 21-35.

Acocks, JPH 1988. Veld types of South Africa. Memoirs of the Botanical Survey of South Africa No. 57, National Botanical Institute, Pretoria.

Allen RG Jensen ME Wright JI and Burman RD 1989. Operational estimates of reference evaporation Agron J 81 650-662

Bainbridge, WR, Scott, DF and Walker, RS 1986. Policy statement for the Drakensberg State Forests. Forestry Branch, Department of Environment Affairs, Pietermaritzburg.

Bartholic, JF, Namken, LN and Wiegand, CL 1972. Aerial thermal scanner to determine temperatures of soils and of crop canopies differing in water stress. *Agronomy Journal* 64: 603-608.

Bate, GC & Walker, BH 1993. Water relations of the vegetation along the Kuiseb River, Namibia. Madoqua 18: 85-91.

Bayne, S 1984. Aerial photography and environmental impact analysis: the potential contribution of comparative interpretation of multi-temporal aerial photographs to environmental impact analysis. Unpublished MSc Thesis, University of Cape Town.

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

Blad, BL and Rosenberg, NJ 1976. Measurement of crop temperature by leaf thermocouple, Infrared thermometry and remotely sensed thermal imagery. *Agronomy Journal* 68: 635-641.

Blad, BL and Rosenberg, NJ 1976. Evaluation of resistance and mass transport evapotranspiration models requiring canopy temperature data. *Agronomy Journal* 68: 764-769.

Boucher, C 1981a. Floristic and structural features of the coastal foreland vegetation south of the Berg River, Western Cape Province, South Africa. In: Proceedings of a symposium on the coastal lowlands of the Western Cape (ed. E Moll), pp 21-26. University of the Western Cape.

Boucher, C 1981b. Dune plumes in the Western Cape. Veld & Flora: 67: 11-13.

Boucher, C 1983. Floristic and structural features of the coastal foreland vegetation south of the Berg River, western Cape Province, South Africa. *Bothalia* 14: 669-674.

Boucher, C 1987. A phytosociological study of transects through the Western Cape coastal foreland, South Africa. Unpublished PhD Thesis, University of Stellenbosch, Stellenbosch.

Boucher, C and Jarman, ML 1977. The vegetation of the Langebaan area, South Africa. *Transactions of the Royal Society of South Africa* 42: 241-272.

Boucher, C and le Roux, A 1993. Dry coastal ecosystems of the South African west coast. In: Dry coastal ecosystems: Africa, America, Asia and Oceania (ed Van der Maarel, E), pp 75-88. Elsevier, Amsterdam.

Boucher, C and Parsons, R 1980. Vegetation. Unpublished report, file CP Estuaries 7/1/1 CW22 Silwerstroom, Environmentek, CSIR, Stellenbosch.

Braune, E, Xu, Y, Conrad, J, van der Voort, I, Colvin, C, Le Maitre, D, van Tonder, DJ, Chiang, WH, Zhang, J, Hughes, S and Pietersen, K 2000. Comprehensive Determination of the Resource Directed Measures: Groundwater Component (Version 1.0). Department of Water Affairs and Forestry, Pretoria.

Brown, CA, Eekhout, S & King, JM 1996. National Biomonitoring programme for riverine ecosystems: Technical considerations and protocol for the selection of reference and monitoring sites. NBP Report Series No 3, Institute for Water Quality Studies, Department of Water Affairs and Forestry, Pretoria.

Brown, KW and Rosenberg, NJ 1973. A resistance model to predict evapotranspiration and its application to a Sugar Beet field. *Agronomy Journal* 65: 341-347.

Burger, C, Everson, CS and Savage, MJ 1999. Comparative evaporation measurements above commercial forestry and sugarcane canopies in the KwaZulu-Natal midlands. In: Ninth South African National Hydrology Symposium (Western Cape): Hydrology and water resources in Southern Africa, 9 pp. November 1999, University of the Western Cape, Bellville.

Caldwell, MM and Richards, JH 1989. Hydraulic lift: water efflux from upper roots improves plant performance. *Oecologia* 79: 1-5.

Caldwell, MM, Dawson, TE and Richards, JH 1998. Hydraulic lift: consequences of water efflux from the roots of plants. *Oecologia* 113: 151-161.

Campbell GS (undated) On-line measurement of potential evapotranspiration with the Campbell Scientific automated weather station. Application note, Campbell Scientific Inc., Dept of Crop and Soil Sciences, Washington State University.

Canadell, J, Jackson, RB, Ehleringer, JR, Mooney, HA, Sala, OE & Schulze, E-D 1996. Maximum rooting depth of vegetation types at the global scale. Oecologia 108: 583-595.

Carlquist, S 1977. Ecological factors in wood evolution: a floristic approach. *American Journal of Botany* 64: 887-896.

Carlson, RE, Yarger, DN and Shaw, RH 1972. Environmental influences on the leaf temperatures of two soybean varieties grown under controlled irrigation. *Agronomy Journal* 64: 224-229.

Cave, L, van der Voort, I and Tredoux, G 1996. Atlantis groundwater management review, 1995/96. Report No. ENV/S-C96070, Cape Water Programme, Environmentek, CSIR, Stellenbosch.

Chehbouni, A, Hartogensis, O, Kerr, YH, Hipps, L, Brunel, J-P, Watts, C, Rodriguez, J, Boulet, G, Dedieu, G De Bruin, H. 1998. Sensible heat flux measurements using a large aperture scintillometer over heterogeneous surface. Paper-1.6, Session 1: Integrated Observations of Semi-Arid Land-Surface-Atmosphere Interactions, Proceedings of the Special Symposium on Hydrology, American Meteorological Society, Phoenix, Arizona, 11-16 Jan 1998. From the following internet address: http://www.tucson.ars.ag.gov/salsa/archive/publications/ams_preprints/chehbouni1.html.

Choudhury, BJ, Reginato, RJ and Idso, SB 1986. An analysis of infrared temperature observations over wheat and calculation of latent heat flux. *Agricultural and Forest Meteorology* 37: 75-88.

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

CMC 2000. Environmental significance mapping. Pilot Release Version 1.1, August 2000. Environmental Management Department, Directorate: Planning, Environment and Housing, Cape Metropolitan Council.

Cole, MM 1986. *The savannas. Biogeography and geobotany*. Academic Press, London.

Cowan, GI (ed.) 1995. Wetlands of South Africa. Department of Environment Affairs and Tourism, Pretoria.

Cowling, RM, Richardson, DM and Mustart, PJ 1997b. Fynbos. In: Vegetation of southern Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 99-130. Cambridge University Press, Cambridge, UK.

Cowling, RM, Richardson, DM and Pierce, SM 1997a. Vegetation of southern Africa. Cambridge University Press, Cambridge, UK.

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

Crombie, DS 1992. Root depth, leaf area and daytime water relations of jarrah (*Eucalyptus marginata*) forest overstorey and understorey during summer drought. *Australian Journal of Botany* 40: 113-122.

Crombie, DS, Tippett, JT & Hill, TC 1988. Dawn water potential and root depth of trees and understorey species in south-western Australia. *Australian Journal of Botany* 36: 621-631.

Daines, A and Low, B 1993. Cape Metropolitan Area: West Coast environmental survey. Unpublished report for the Cape Metropolitan Council, National Botanical Institute, Cape Town.

Dallas, HF and Day, JA 1993. The effect of water quality variables on riverine ecosystems: a review. Report No. TT 61/93, Water Research Commission, Pretoria.

Davies, BR, OKeeffe, JH, Snaddon, CD 1993. A synthesis of the ecological functioning, conservation and management of South African River Ecosystems. Report No. TT 62/93, Water Research Commission, Pretoria.

Davies, BR, OKeeffe, JH, Snaddon, CD 1993. A synthesis of the ecological functioning, conservation and management of South African River Ecosystems. Report No. TT 62/93, Water Research Commission, Pretoria.

Davis, SD & Mooney, HA 1986. Water use patterns of four co-occurring chaparral shrubs. *Oecologia* 70: 172-177.

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

Davis, SD and Mooney, HA 1986. Water use patterns of four co-occurring chaparral shrubs. Oecologia 70: 172-177.

Dawson, TE 1993. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. Oecologia 95: 565-574.

Dawson, TE 1993a. Hydraulic lift and water use by plants: implications for water balance, performance and plant-plant interactions. *Oecologia* 95: 565-574.

Dawson, TE 1993b. Woodland water balance. *Trends in Ecology and Evolution* 8: 120-121.

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

De Vries, JJ, Seloalo, ET and Beekman, HE 2000. Groundwater recharge in the Kalahari, with reference to palaeo-hydrologic conditions. Journal of Hydrology 238: 110-123.

Deacon, HJ, Jury, MR and Ellis, F 1992. Selective regime and time. In: he ecology of Fynbos: nutrients, fire and diversity (Cowling, RM ed.), pp 6-22. Oxford University Press, Cape Town.

Deall, GB, Scheepers, JC and Schutz, CJ 1989. The vegetation ecology of the Eastern Transvaal escarpment in the Sabie area. 1. Physical environment. Bothalia 19: 53-67.

Dodd, J & Bell, DT 1993. Water relations of understorey shrubs in a Banksia woodland, Swan Coastal Plain, Western Australia. Australian Journal of Ecology 18: 295 305 (abstract).

Dodd, J, Heddle, EM, Pate, JS & Dixon, KW 1984. Rooting patterns of sandplain plants and their functional significance. In: *Kwongan: plant life of the sandplain* (eds JS Pate & JS Beard), pp 146-177. University of Western Australia press, Nedlands, Western Australia.

Du Toit, IM 1997. Management options in the Atlantis aquifer. Unpublished MSc thesis, Institute for Groundwater Studies, University of the Free State, Bloemfontein.

Duthie, A (compiler) 1999. Discussion document for the development of a method for determining the wetland component of the preliminary reserve. Copy supplied by e-mail 2 July 1999.

DWAF 1996. Water Law Principles. Discussion document. Department of Water Affairs and Forestry, Pretoria. April 1996.

Dye, P and Moses, G 1999. Comparing yearlong evapotranspiration from a wattle thicket and a fynbos community in two Western Cape riparian sites. In: Proceedings of the Ninth South African National Hydrology Symposium (Western Cape): Hydrology and water resources in Southern Africa, 9 pp. November 1999, University of the Western Cape, Bellville.

Dye, PJ 1996. Response of Eucalyptus grandis trees to soil water deficits. Tree Physiology 16: 233-238.

Dye, PJ and Olbrich, BW 1993. Estimating transpiration from six-year-old Eucalyptus grandis trees: development of a canopy conductance model and comparison with independent sap flux measurements. *Plant, Cell and Environment* 16: 45-53

Dye, PJ and Poulter, AG, 1991. An investigation of sub-soil water penetration in the Mokobulaan research catchments, South-eastern Transvaal. *South African Forestry Journal*, 161: 31-34.

Dye, PJ, Olbrich, BW and Calder, IR 1992. A comparison of the heat pulse method and Deuterium tracing method for measuring transpiration from Eucalyptus grandis trees. *Journal of Experimental Botany* 43: 337-343.

Eekhout, S, King, JA and Wackernagel, A 1997. Classification of South African Rivers. Volume 1. Final Report. Department of Environmental Affairs and Tourism, Pretoria.

ESRI, *ArcGIS help documentation* 2001. Environmental Systems Research International, Redlands, California, USA. http://www.esri.com

Everson, CS, Molefe, GL and Everson, TM 1998. Monitoring and modelling components of the water balance in a grassland catchment in the summer rainfall area of South Africa. WRC report no. 493/1/98. Water Research Commission, Pretoria.

FIEC 1995. Guidelines for environmental conservation management in commercial forests in South Africa. Forest Industry Environmental Committee, Forest Owners Association, Johannesburg.

FIEC 1999. A practical procedure for the delineation of riparian/wetland habitats for land use practices in South Africa. Draft document for discussion. Copy obtained from Mr P Gardiner, Mondi, Pietermaritzburg.

Field, C, Berry, JA and Mooney, HA 1982. A portable system for measuring carbon dioxide and water vapour exchange of leaves. *Plant, Cell and Environment* 5: 179-186.

Fleischer, JNE and Eskes, JNT 1992. Optimisation and management of the Atlantis groundwater resources. CSIR Internal Report N0 11/92, Cape Water Programme, CSIR, Stellenbosch.

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

Frissel, CA, Liss, WJ, Warren, CE and Hurley, MD 1986. A hierarchical framework for stream classification viewing streams in context. Environmental Management 10: 199-214.

Garcia-Carreño, FL, Troyo-Dieguez, E and Ochoa, JL 1992. Relationships between saline groundwater, soil, and leaf tissue composition of the phreatophytic mezquite. *Ground Water* 30: 676-682.

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

Haigh, H, 1966. Root development in the sandy soils of Zululand. *Forestry in South Africa* 7:31-36.

Harding, GB and Bate, GC 1991. The occurrence of invasive Prosopis species in the north-western Cape, South Africa. South African Journal of Science 87: 188-192.

Hatfield, JL, Reginato, RJ and Idso, SB 1984. Evaluation of canopy temperature-evapotranspiration models over various crops. *Agricultural and Forest Meteorology* 32: 41-53.

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

Hatton, T, Reece, P, Taylor, P and McEwan, K 1998. Does leaf water efficiency vary among eucalypts in water-limited environments. *Tree Physiology* 18: 529-536.

Heijnis, CJ, Lombard, AT, Cowling, RM and Desmet, PG 1999. Picking up the pieces: a biosphere reserve framework for a fragmented landscape – the coastal lowlands of the Western Cape, South Africa. Biodiversity and Conservation 8: 471-496.

Heilman, JL and Kanemasu, ET 1976. An evaluation of a resistance form of the energy balance to estimate evapotranspiration. *Agronomy Journal* 68: 607-611.

Heinecken, TJE 1987. Coastal study of Silwerstroomstrand, Atlantis. Report No. C/SEA 8733, Division of Environment, Water and Forestry Technology, CSIR, Stellenbosch.

Heineken, TJE and Nicholas, J, 1984. Atlantis: Coastal Development. Unpublished report, file CP Estuaries 7/1/1 CW22 Silwerstroom, Environmentek, CSIR, Stellenbosch.

Higgins, KB, Lamb, AJ and Van Wilgen, BW 1987. Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek Valley, south-western Cape Province. South African Journal of Botany 53: 249-257.

Higgins, KB, Lamb, AJ and Van Wilgen, BW 1987. Root systems of selected plant species in mesic mountain fynbos in the Jonkershoek Valley, south-western Cape Province. South African Journal of Botany 53: 249-257.

Hill, RJ 1997. Algorithms for obtaining atmospheric surface-layer fluxes from scintillation measurements. *Journal of Atmospheric and Oceanic Technology* 14: 456-467.

Hill, RJ, Ochs, GR and Wilson, JN 1992. Measuring surface-layer fluxes of heat and momentum using optical scintallation. Boundary Layer Meteorology 58: 391-408.

Hodgson, FDI 1986. Geohydrology. In: The Karoo biome: a preliminary systhesis. Part 1 – physical environment (ed RM Cowling), pp 84-91. South African National Scientific Programmes Report No. 124, National Research Foundation, Pretoria.

Howard, SB, Ong, CK, Black, CR and Khan, AAH 1998. Using sap-flow gauges to quantify water uptake by tree roots from beneath the crop rooting zone in agroforestry systems. *Agroforestry Systems* 35: 15-29.

Jackson, RB, Canadell, J, Ehleringer, JR, Mooney, HA, Sala, OE & Schulze, E-D 1996. A global analysis of root distributions for terrestrial biomes. Oecologia 108: 389-411.

Jackson, RD and Idso, SB 1969. Ambient temperature effects in infrared thermometry. *Agronomy Journal* 61: 324-325.

Jarbeau, JA, Ewers, FW and Davis, SD 1995. The mechanism of water stress-induced embolism in two species of chaparral shrubs. *Plant, Cell and Environment* 18: 189-196.

Jarvis, PG and McNaughton, KG 1986. Stomatal control of transpiration: scaling up from leaf to region. *Advances in Ecological Research* 15: 1-49.

Jennings, C 1974. The HydroGeology of Botswana. Unpublished PhD thesis, University of Natal.

Jewitt, GPW, Heritage, GL, Weeks, DC, Mackenzie, JA, van Niekerk, A, Görgens, AHM, O'Keeffe, Rogers, K and Horn, M 1998. Modelling abiotic-biotic links in the Sabie River. Report No. 777/1/98, Water Research Commission, Pretoria.

Jobst, P 1996. Investigating water problems of *Fairherbia albida* along the Knisels River, Namibia. Botang Honours Thesis, University of Cape Town.

Joubert, AR and Hurly, PR 1994. Groupring South African rivers using flow-derived variables. In: Classification of rivers and environmental health indicators. Proceedings of a joint South African • Australian workshop, Cape Town, February 1994 (Uys, MC ed.), pp 27-42. Report No. TT 63/94, Water Research Commission, Pretoria.

Jürgens, N, Burke, A, Seely, MK and Jacobson, KM 1997. Desert. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 189-214. Cambridge University Press, Cambridge, UK.

Kelliher, FM, Leuning, R and Schulze, E-D 1993. Evaporation and canopy characteristics of coniferous forests and grasslands. *Oecologia* 95: 153-163.

Khanzada, AN, Morris, JD, Ansari, R, Slavich, PG and Collopy, JJ 1998. Groundwater uptake and sustainability of *Acacia* and *Prosopis* plantations in Southern Pakistan. *Agricultural Water Management,* 36: 121-139.

King, LC 1942. South African scenery. A text book of geomorphology. Oliver and Boyd Ltd, London.

Kleynhans, CJ and Hill, L 1999. Preliminary Ecoregion Classification System for South Africa. Version 1.0, 24 September 1999. Appendix R1, Resource Directed Measures for Protection of Water Resources: River Ecosystems (ed. H MacKay and L Guest). Copy downloaded from the Department of Water Affairs internet site on Resource Directed Measures.

Kotze, DC 1996. How wet is a wetland? An introduction to wetland hydrology, soils and landforms. WETLAND-USE Booklet 1, Share-Net, Wildlife and Environment Society of South Africa.

Kotze, DC, Klug, JR, Hughes, JC and Breen, CM 1996. Improved criteria for classifiying hydric soils in South Africa. South African Journal of Plant and Soil 13: 67-73.

Kozlowski, TT 1982. Water supply and tree growth. *Forestry Abstracts* 43: 57-95.

Kruger, GP 1983. Terrain morphology map of South Africa. Institute for Soil, Climate and Water, Agricultural Research Council, Pretoria.

Lageat, Y and Robb, LJ 1984. The relationship between structural landforms, erosion surfaces and the geology of the Archaean granite basement in the Barberton region, Eastern Transvaal. Transaction of the Geological Society of South Africa 87: 141-159.

Le Maitre, DC, Scott, DF and Colvin C 1999. A review of information on interactions between vegetation and groundwater. Water SA 25: 137-152.

Le Maitre, DC, van Wilgen, BW, Chapman, RA & McKelly, DH 1996. Invasive plants in the Western Cape, South Africa: modelling the consequences of a lack of management. Journal of Applied Ecology 33: 161-172.

Lillesand, T.M. and Kiefer, R.W. *Remote sensing and image interpretation, 3rd edition*, (1994), John Wiley and Sons inc. New York, Chichester, Brisbane, Toronto, Singapore.

Linacre ET 1977. A simple formula for estimating evaporation rates in various climates using temperature data alone. *Agricultural Meteorology* 18: 409-424.

Low, AB and Rebelo, AG 1996. Vegetation of South Africa, Lesotho and Swaziland. Department of Environmental Affairs and Tourism, Pretoria.

Lubke, RA, Avis, AM, Steinke, TD and Boucher, C 1997. Coastal vegetation. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 300-321. Cambridge University Press, Cambridge, UK.

Maze, KE and Rebelo, AG 1999. Core conservation areas on the Cape Flats. FCC Report 99/1, Flora Conservation Committee, Botanical Society of South Africa, Kirstenbosch.

Midgley, GF & Bösenberg, J De W 1990. Seasonal and diurnal plant water potential changes in relation to water availability in the mediterranean climate western Karoo. South African Journal of Ecology 1: 45-52.

Midgley, JJ, Cowling, RM, Seydack, AHW and van Wyk, GF 1997. Forest. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 278-299. Cambridge University Press, Cambridge, UK.

Midgley, JJ, Talma, S, Scott, DF, Olbrich, BW and van Wyk, GF 1994. Analysis of stable isotopes of xylem water from plantation trees in E. Transvaal and Zululand indicate they utilized ground water during drought of, 1992. *South African Forestry Journal* 170: 33-36.

Milton, S and Dean, R 1999. Big old camelthorn trees. Key resource for Kalahari Wildlife. African Wildlife 53(5): 10-12.

Milton, SJ 1990. Life styles of plants in four habitats in an arid Karoo shrubland. South African Journal of Ecology 1: 63-72.

Milton, SJ, Yeaton, RI, Dean, WRJ and Vlok, JHJ 1997. Succulent karoo. In: Vegetation of southern Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 131-166. Cambridge University Press, Cambridge, UK.

Morrison, ML, Tennant, T & Scott, TA 1994. Environmental auditing. Laying the foundation for a comprehensive program of restoration of wildlife habitat in a riparian floodplain. Environmental Management 18: 939-955.

Naiman, RJ, Decamps, H & Pollock, M 1993. The role of riparian corridors in maintaining regional biodiversity. Ecological Applications 3: 209-212.

NASA 19*99 EOS Reference Handbook: A Guide to NASA's Earth Science Enterprise and the Earth Observing System* – http://eos.nasa.gov (1999). NP–1999–08–134-GSFC

NASA Earth Observing System, *ASTER information brochure*. 2000. Jet Propulsion Laboratory/Goddard Space Centre.

NCC 1999. Desktop methodology to identify groundwater-dependent ecosystems. Report compiled for the Nature Conservation Council of NSW Inc. by PPK Environment & Infrastructure Pty Ltd.

Nilsen, ET, Sharifi, MR & Rundel, PW 1984. Comparative water relations of phreatophytes in the Sonoran desert of California. *Ecology* 65: 767-778.

O'Connor, TG 2001. Effect of small catchment dams on downstream vegetation of a seasonal river in semi-arid African savanna. Journal of Applied Ecology 38: 1314-1325.

O'Connor, TG and Bredenkamp, GJ 1997. Grassland. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 215-257. Cambridge University Press, Cambridge, UK.

Olbrich, BW 1991. The verification of the heat pulse velocity technique for estimating sap flow in Eucalyptus grandis. *Canadian Journal of Forest Research* 21: 836-841.

Omernik, JM 1987. Ecoregions of the conterminous United States. Annals of the Association of American Geographers 77:118-125.

Palmer, AM and Hoffman, MT 1997. Nama karoo. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 167-188. Cambridge University Press, Cambridge, UK.

Pammenter, NW and vander Willigen, C 1998. A mathematical and statistical analysis of the curves illustrating vulnerability of xylem to cavitation. *Tree Physiology* 18: 589-593.

Partridge, TC 1997. Evolution of landscapes. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 1-20. Cambridge University Press, Cambridge, UK.

Partridge, TC and Maud, RR 1987. Geomorphic evolution of southern Africa since the Mesozoic. South African Journal of Geology 90: 179-208.

Pate, JS, Jeschke, WD and Aylward MJ 1995. Hydraulic architecture and xylem structure of the dimorphic root systems of south-west Australian species of Proteaceae. Journal of Experimental Botany 46: 907-915.

Pate, JS, Jeschke, WD and Aylward MJ 1995. Hydraulic architecture and xylem structure of the dimorphic root systems of south-west Australian species of Proteaceae. Journal of Experimental Botany 46: 907-915.

Pearcy, R.W., Schulze, E.-D. and Zimmerman, R. 1989. Measurement of transpiration and leaf conductance. In: Plant Physiological Ecology. Pearcy, RW, Ehleringer, J, Mooney, HA and Rundel, PW (eds.). Chapman and Hall, London.

Pockman, WT and Sperry, JS 1997. Freezing induced xylem cavitation and the northern limit of *Larrea tridentata.* Oecologia 109: 19-27.

Pockman, WT, Sperry, JS and O'Leary, JW 1995. Sustained and significant negative water pressure in xylem. Nature 378: 715-716.

Pott, RMcC 1997. Plantation forestry in South Africa and its impact on biodiversity and water. South African Forestry Journal 180: 45-48.

Price, JC 1980. The potential of remotely sensed thermal infrared data to infer surface soil moisture and evaporation. *Water Resources Research* 16: 787-795.

Rastetter, EB, King, AW, Cosby, BJ, Hornberger, GM, O'Neill, RV and Hobbie, JE 1992. Aggregating fine-scale ecological knowledge to model coarser-scale attributes of ecosystems. *Ecological Applications* 2: 55-70.

Richards, JH and Caldwell, MM 1987. Hydraulic lift: substantial nocturnal water transport between soil layers by *Artemisia tridentata* roots. *Oecologia* 73: 486-489.

Richardson, D. M., van Wilgen, B. W., Le Maitre, D. C., Higgins, K.B., Forsyth, G.G. *A computer based system for fire management in the mountains for the Cape Province, South Africa.* 1994. International Journal of Wildland Fire, 4 (1), 17 – 32.

Richardson, DM and Kruger, FJ 1990. Water relations and photosynthetic characteristics of selected trees and shrubs of riparian and hillslope in the south-western Cape Province, South Africa. South African Journal of Botany 56: 214-225.

Richardson, DM, Macdonald, IAW, Holmes, PM and Cowling, RM 1992. Plant and animal invasions. In: The ecology of fynbos. Nutrients, fire and diversity (Cowling, R.M. ed.), pp 271-308. Oxford University Press, Cape Town.

Ritchie, GA and Hinckley, TM 1975. The pressure chamber as an instrument for ecological research. *Advances in Ecological Research* 9: 165-254.

Rodgers, KH 1997. Freshwater wetlands. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 322-347. Cambridge University Press, Cambridge, UK.

Rowntree, KM and Wadeson RA 1999. A hierarchical geomorphological model for the classification of selected South African rivers. Report No. 497/1/99, Water Research Commission, Pretoria

Sala, A, Smith, SD & Devitt, DA 1996. Water use by Tamarix ramosissima and associated phreatophytes in a mojave desert floodplain. *Ecological Applications* 6: 888-898.

Sandström, K 1996. Hydrochemical deciphering of streamflow generation in semi-arid East Africa. *Hydrological Processes* 10: 703-720.

Sappi 1998. Planning: Identification of Wetlands and Rivers. Sappi Best Environmental Practice Guidelines dated 24/06/98. Copy supplied by Dr J Scotcher, Sappi, Johannesburg.

Savage, MJ, Everson, CS and Metelerkamp, BR 1997. Evaporation measurement above vegetated surfaces using micrometeorological techniques. Report No. 349/1/97, Water Research Commission, Pretoria.

Scholes, RJ & Walker, BH 1993. *An African savanna. Synthesis of the Nylsvley study.* Cambridge University Press, Cambridge.

Scholes, RJ 1997. Savanna. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 258-277. Cambridge University Press, Cambridge, UK.

Schulze, E-D, Hal, AE, Lange, OT and Walz, H 1982. A portable steady-state porometer for measuring the carbon dioxide and water vapour exchanges of leaves under natural conditions. *Oecologia* 53: 141-145.

Schulze, RE 1995. Hydrology and agrohydrology. A text to accompany the ACRU 3.00 agrohydrological modelling system. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Schulze, RE, Maharaj, M, Lynch, SD, Howe, BJ and Melvil-Thomson 1997. South African atlas of agrohydrology and –climatology. Report No. TT 82/96, Water Research Commission, Pretoria.

Scott, DF & Le Maitre, DC 1998. The interaction between vegetation and groundwater: research priorities for South Africa. Report No. 730/1/98, Water Research Commission, Pretoria.

Scott, DF and Lesch, W 1995b. The water yield gains obtained from clearfelling riparian zone vegetation. Proc. 7th South African National Hydrology Symposium; Grahamstown, September 1995.

Scott, DF and Lesch, W 1997. Streamflow responses to afforestation with Eucalyptus grandis and Pinus patula and to felling in the Mokobulaan experimental catchments, Mpumalanga Province, South Africa. Journal of Hydrology, 199: 360-377.

Scott, DF, 1993. Rooting strategies by plantation trees on deep sands. Proc. Sixth South African National Hydrological Symposium, pp. 155-162, September, 1993, Pietermaritzburg. Department of Agricultural Engineering, University of Natal, Pietermaritzburg.

Scott, L, Anderson, HM and Anderson, JM 1997. Vegetation history. In: Vegetation of South Africa (eds RM Cowling, DM Richardson and SM Pierce), pp 62-84. Cambridge University Press, Cambridge.

Shafroth, PB, Stromberg, JC and Patten, DT 2000. Woody riparian vegetation response to different alluvial aquifer water table regimes. *Western North American Naturalist* 60: 66-76.

Shaughnessy, GL 1980. Historical ecology of alien woody plants in the vicinity of Cape Town, South Africa. Unpublished PhD study, Environmental Studies, University of Cape Town.

Shaughnessy, GL 1986. A case study of some woody plant introductions to the Cape Town area. In: The ecology and management of biological invasions in South Africa (eds. Macdonald, IAW, Kruger, FJ and Ferrar, AA), pp 37-43. Oxford University Press, Cape Town.

Siegfried, WR 1981. Trophic structure of some communities of fynbos birds. In: Proceedings of a symposium on the coastal lowlands of the Western Cape (ed. E Moll), pp 31-51. University of the Western Cape.

Smith, DM and Allen, SJ 1996. Measurement of sap flow in plant stems. *Journal of Experimental Botany* 47: 1833-1844.

Smith, RE 1990. Comparison of the plant water relations of Cunonia capensis and Pittosporum undulatum in a riparian woodland in the south-western Cape. South African Journal of Botany 56: 409-412.

Smith, RE 1992. The heat pulse velocity technique for determining water uptake of Populus deltoids. South African Journal of Botany 58: 100-104.

Smith, RE, Moses GR and Versfeld, DB 1992. Verification of the Heat Pulse Velocity Technique for Acacia mearnsii. South African Forestry Journal 163: 1-4.

Sperry, JS, Tyree, MT and Donelly, JT 1998. A method for measuring hydraulic conductivity and embolism in xylem. *Plant Cell and Environment* 11: 35-40.

Stanford, JA and Ward, JV 1993. An ecosystem perspective of alluvial rivers: connectivity and the hyporhoeic zone. Journal of the North American Benthological Society 12: 48-60.

Stephenson, NL 1990. Climatic control of vegetation distribution: the role of the water balance. *American Naturalist* 135: 649-470.

Stock, WD and Allsop, N 1992. Functional perspective of ecosystems. In: The ecology of fynbos. Nutrients, fire and diversity (Cowling, R.M. ed.), pp 239-259. Oxford University Press, Cape Town.

Stone, EL and Kalisz, PJ 1991. On the maximum extent of roots. Forest Ecology and Management 46: 59-102.

Stone, LR and Horton, ML 1974. Estimating evapotranspiration using canopy temperatures: field evaluation. *Agronomy Journal* 66: 450-455.

Thorburn, PJ, Hatton, TJ & Walker, GR 1993. Combining measurements of transpiration and stable isotopes of water to determine groundwater discharge from forests. *Journal of Hydrology* 150: 563-587.

Tyree, MT and Ewers, EW 1991. Hydraulic architecture of trees and other woody plants. Tansley review No. 34. *New Phytologist* 119: 345-360.

Tyree, MT and Sperry, JS 1989. Vulnerability of xylem to cavitation and embolism. *Annual Review of Plant Physiology and Molecular Biology* 40: 19-38.

Unland, HE, Arain, AA, Harlow, C, Houser, PR, Garatusa-Payan, J, Scott, P, Sen, OL and Shuttleworth, WJ 1998. Evaporation from a riparian system in a semi-arid environment. *Hydrological Processes* 12: 527-542.

Uys, MC (ed.) 1994. Classification of rivers and environmental health indicators. Proceedings of a joint South African • Australian workshop, Cape Town, February 1994. Report No. TT 63/94, Water Research Commission, Pretoria.

Valentini, R, Scarascia Mugnozza, GE, De Angelis, P and Bimbi, R 1991. An experimental test of the eddy correlation technique over a Mediterranean macchia canopy. *Plant, Cell and Environment* 14: 987-994.

Valett, HM, Fisher, SG, Grimm, NB and Camill, P 1994. Vertical hydrologic exchange and ecological stability of a desert stream ecosystem. Ecology 75: 548-560.

Van Tonder, GJ & Kirchner, J 1990. Estimation of natural groundwater recharge in the Karoo aquifers of South Africa. Journal of Hydrology 121: 395-419.

Vander Willigen, C and Pammenter, NW 1998. Relationship between growth and xylem hydraulic characteristics of clones of *Eucalyptus* spp. at contrasting sites. *Tree Physiology* 18: 595-600.

Vegter, JR 1995. An explanation of a set of national groundwater maps. Report No. TT 74/95, Water Research Commission, Pretoria.

Vegter, JR 2001. Groundwater development in South Africa and an introduction to the hydrogeology of groundwater regions. Report No TT 134/00, Water Research Commission, Pretoria.

Vegter, JR, 1992. De Aar's Ground-water supply: a digest of the past and an outlook for the future. Unpublished consultancy report, GH 3775, to the Directorate of Geohydrology, Department of Water Affairs and Forestry, Pretoria.

Verma, SB, Rosenberg, NJ, Blad, BL and Baradas, MW 1976. Resistance-energy balance method for predicting evapotranspiration: determination of boundary layer resistance and evaluation of error effects. *Agronomy Journal* 68: 776-782.

Versfeld, DB and Van Wilgen, BW 1986. Impact of woody aliens on ecosystem properties. In: The ecology and management of biological invasions in South Africa (eds. Macdonald, IAW, Kruger, FJ and Ferrar, AA), 239-246. Oxford University Press, Cape Town.

Walker, BH and Langridge, JL 1996. Modelling plant and soil water dynamics in semi-arid ecosystems with limited site data. Ecological Modelling 87: 153-167.

Ward, JD & Breen, CM 1983. Drought stress and the demise of *Faidherbia albida* along the lower Kuiseb River, central Namib Desert: preliminary findings. *South African Journal of Science* 79: 444-447.

Weaver, JMC and Talma, AS 2000. Deep flowing groundwater in the Table Mountain Group quartzite. In: Groundwater: past achievements and future challenges (eds. O Sililo *et al.*) pp 359-364. AA Balkema, Rotterdam.

Westoby, M, Walker, B and Noy-Meir, I 1989. Opportunistic management for rangelands not at equilibrium. Journal of Range Management 42: 266-274.

Winter, TC, Harvey, JW, Franke, OL and Alley, WM 1999. Ground water and surface water: a single resource. US Geological Survey Circular No. 1139, Denver Colorado.

Wullschleger, SD, Meinzer, FC and Vertessy, RA 1998. A review of whole-plant water use studies in trees. *Tree Physiology* 18: 499-512.

Zhang, J, van der Voort, I, Weaver, J and Tredoux, G in prep. Numerical models for Atlantis aquifer. CSIR Report ENV-S-I 2001-10.

GLOSSARY

Actual evaporation

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

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 IKONOS1. 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.

Alluvial aquifer	An aquifer formed of unconsolidated sediments deposited by a river or stream; typically occurring beneath or alongside a current channel, or in an buried old or paleo-channel of the river.
Annual plant	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
Aquatic ecosystem	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.
Aquifer	A geological formation which has structures or textures that hold water or permit appreciable water movement through them (Water Act, 1998).
Biodiversity	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).
Biome	A broad ecological unit representing major life zones of large areas. In South Africa these are defined mainly by vegetation structure and climate (Low and Rebelo, 1996).
Capillary fringe	The lower division of the zone of aeration (vadose zone) that overlies the zone of saturation and in which the pressure of water in the interstices is less than atmospheric (McGraw-Hill, 1978).
Coastal forest	Medium to tall forest vegetation dominated by evergreen trees, climbers and shrubs, often associated with coastal lakes and swamps. Distributed from Alexandria to the Mocambique 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).
Ecosystem	An interconnected and interacting system comprising living organisms - including animals, plants, fungi, and microorganisms - and their non-living environment.

Embolism — 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. Embolisms block the vessels and stop water transport though them. When a large proportion of these vessels are blocked by embolisms the plant cannot supply enough water to its leaves to prevent wilting and death.

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 rainfalll. 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., 19*94). 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.

IKONOS 1 — 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 it's 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 Landsats 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 multispectral 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. Landsat7 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 goundwater 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 water table.

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 SPOT 2 in, 1990 and SPOT3 in, 1996. SPOT 3 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.

Thicket

A very variable vegetation type dominated by evergreen shrubs and trees; vines are often common; in the more open forms the gaps between the shrubs are dominated by annuals and succulents as is the pioneer stage in dune areas. Dune thicket is also known as strandveld.

Transpiration

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