THE INTERACTION BETWEEN VEGETATION AND GROUNDWATER: RESEARCH PRIORITIES FOR SOUTH AFRICA

by

D.F. Scott and D.C. Le Maitre

CSIR Division of Water, Environment and Forestry Technology
Stellenbosch

Water, Environment and Forestry Technology
CSIR

CSIR Report No. ENV/S-C 97161

Report to the Water Research Commission on the project K5/730 entitled "Development of a research strategy on the interaction between vegetation and groundwater"

WRC Report No. 730/1/98
ISBN 1 86845 398 7

May 1998

EXECUTIVE SUMMARY

Background and Motivation

There is a growing appreciation in South Africa that the conceptual separation of surface and groundwater is artificial, and that these systems are but expressions of the same precious resource. As the limits of water resources in South Africa become more obvious, and with the current revision of South African water law aiming to providing all water with a consistent status in law, there is an ever more pressing need to understand the complete cycle of water in the environment.

The new approach requires a much greater understanding of the role of vegetation in the hydrological cycle, specifically the neglected area of interactions between vegetation and groundwater. This project aimed to review and organise the available information on this subject, and to prepare an initial strategy to guide research decision making on this topic.

Several recent developments have focussed attention on our lack of information on, and the importance of, vegetation and groundwater interactions in South Africa in the recent past. Measurement and modelling of the recharge on the Atlantis and Zululand coastal aquifers have highlighted the role of vegetation cover on recharge, and even abstraction from shallow groundwater. Farmers in the karoo felt that the exploitation of groundwater for urban development was having a negative effect on the productivity of their veld. Efforts were being made to utilise the greater water use characteristics of trees to reduce the volumes of acid water drainage out of mined land in the Mpumalanga highveld. The new policy on water in South Africa provides for human use and environmental reserves, which should ensure that these requirements are considered when the exploitation of aquifers is being planned.

Objectives of the project

The objectives of the research programme were as follows:

- Explore the substance of the interaction between vegetation and groundwater by gathering evidence from the published literature and gathering evidence from South African experience.
- The emphasis will be on understanding and estimating the impacts of vegetation on groundwater recharge, and groundwater depletion and the potential impacts of groundwater extraction on vegetation health, at the landscape to regional scale

- Develop hypotheses as a theoretical basis for understanding the processes of vegetation-groundwater interactions for different climatic, geomorphological and vegetation types in South Africa.

- Convene a national workshop of a cross-section of relevant experts from various disciplines to workshop the status of our knowledge, classify vegetation-groundwater situations, and prioritise research topics.

- Produce a research strategy for relevant issues in this inter-disciplinary research area.

The South African Setting

Roughly 13% of all water used in South Africa is estimated to come from groundwater, and over the more arid western two-thirds of the country groundwater is the sole or primary source of water. Elsewhere, in South Africa many rural communities are dependent for their domestic needs on springs and run-of-river water, both of which, during the dry season, are forms of groundwater discharge.

Over about 90% of the surface of South Africa, groundwater occurs in secondary aquifers. These include groundwater contained in fractures (faults and joints) in hard rocks and to some extent pores in the weathered zone (saprolite) of these rocks, and groundwater in dolomite and limestone. Apart from this latter type, therefore, groundwater storage capacity is limited and tends to occur in localised cells rather than regional aquifers.

Over the remainder of the country groundwater occurs in three different types of primary aquifers, namely;

- Narrow, discontinuous strips of alluvium along some rivers. These are important aquifers but of very limited and local extent, e.g. Limpopo, and Buffels Rivers.

- Recent (Cainozoic) unconsolidated and partially consolidated sand deposits fringing the coasts, e.g. Northern Zululand, Cape Flats and Atlantis.

- The extensive Kalahari sand deposits of Tertiary Age, forming important primary aquifers particularly where pre-Kalahari Valleys have been filled.

Main findings from an analysis of literature and anecdotal information

1. A change in vegetation, from say grassland to forest, can have a large effect on recharge. The size of this effect is dominated, in South Africa, by the additional transpiration of the more complex vegetation type while interception increases are less important.
2. Vegetation largely determines the amount of net rainfall, and may also influence infiltration, percolation and deep drainage, and the available storage capacity of systems. All these factors combine to determine potential recharge. The effects of vegetation can therefore be both positive and negative.
3. Deep rooting by plants is probably more prevalent than was previously suspected.

4. Recharge modelling (estimates) ought not assume vegetation is a constant factor: the nature of the land cover can have a large influence on recharge.

5. In the higher rainfall (Eastern Seaboard) regions of South Africa, many groundwater and surface water systems are in short-term hydraulic continuity - small storage capacity and short residence times underground - therefore base flow in streams is a fairly direct indicator of groundwater levels. Groundwater exploitation in these regions may have immediate effects on surface water yields.

6. Of the natural biomes of South Africa, it is probably within the savanna biome that the largest changes to groundwater resources may be effected by changes in biomass.

7. The sensitivity of phreatophytes to water table changes varies; some are highly adaptable while others are vulnerable to small changes in groundwater levels.

8. Groundwater abstraction from alluvial aquifers in semi-arid to arid areas of South Africa can be expected to impact riparian vegetation communities, as there is a direct link between the aquifer and associated vegetation.

9. Coastal aquifers have a relatively high recharge rates, shallow water tables and short residence times. The potential for significant interactions with vegetation, both through an effect on recharge and by means of direct abstraction of groundwater by plants appears to be high.

10. Environmental concerns may limit the development of large groundwater exploitation schemes because of our inability to satisfactorily predict "downstream" impacts. Environmental impact assessments should apply an understanding of the flow paths and residence times of groundwater, in order to predict the effects on plants.

11. The requirements of ecosystems that depend on groundwater are poorly documented in South Africa, yet this is an issue that we shall increasingly be called on to address. The concept might be confined to surface water systems at present but it seems likely that such systems are more dependent on groundwater reserves than is widely appreciated.

Research priorities

The following list of research priorities was developed at a multi-disciplinary workshop held in terms of this project (see Appendix 1) as moderated by the reviews of literature and anecdotal information and expert opinion. These topics are in rough order of importance.

- Identify and map groundwater dependent communities (hot spots). For determination of groundwater dependent vegetation use of remotely sensed multi-spectral images is recommended.

- Development of a classification scheme to guide/assist evaluation of the importance of groundwater-vegetation interactions and vulnerability to impacts.

- Scientific field investigations aimed at improving the understanding and quantification of the processes involved (isotope studies, monitoring the affects of changing groundwater/vegetation conditions, alien vegetation removal, etc). There are few examples of detailed studies in South Africa. Applied research in this area is therefore necessary to improve land-use and groundwater management and conservation, especially in the light of expected changes to the Water Law, that will require a holistic approach to be taken.

- Development of guidelines and/or expert systems to support policy makers and planners to assess the importance of groundwater-vegetation interactions and impact vulnerability. There is a need, at the national policy-making and at the regional and local planning level, for tools to support decision-making aimed at managing the hydrological cycle as a whole.

- GIS maps (regional and local scales) of bio-hydrogeological response units and hot-spots.

- Quantitative modelling of interactions: one dimensional (1D), 2D and spatially explicit soil-vegetation-atmosphere transfer (SVAT) models with appropriate capacity to deal with a groundwater component, as an adjunct to original process studies. The policy guidelines could emerge iteratively from this process. Further elaboration, refinement and testing of the models would lead to successive improvements.

- Publication of a non-technical booklet to increase general public awareness of the importance of groundwater-vegetation interactions and the potential vulnerability of ecosystems or aquifers.

ACKNOWLEDGEMENTS

The research in this report emanated from a project funded by the Water Research Commission entitled:

A research strategy on the interaction between vegetation and groundwater.

The Steering Committee responsible for this project consisted of the following persons:

Mr H Maaren	Water Research Commission (Chairman)
Mr AG Reynders	Water Research Commission
Prof D Hughes	Institute for Water Research, Rhodes University
Mr E Braune	Directorate Geohydrology, Department Water Affairs & Forestry
Mr E van Wyk	Directorate Geohydrology, Department Water Affairs & Forestry
Mr B Rawlins	University of Zululand
Mr R Meyer	CSIR Division of Water Environment and Forestry Technology (formerly Ematek)
Dr G Tredoux	CSIR, Division of Water, Environment and Forestry Technology (formerly Watertek)
Dr R Scholes	CSIR, Division of Water, Environment and Forestry Technology (formerly Forestek)
Prof F Hodgson	Institute for Groundwater Studies, University of Orange Free State
Dr V Cogho	Chamber of Mines (represented by a colleague)
Mr J Easton	Chamber of Mines
Mr AC Fritz	Water Research Commission (Committee Secretary)

In addition, the revision of the draft report was greatly improved by the inclusion of the comments of Mr Eberhard Braune, Mr John Weaver, Mr JR Vegter, Dr JSV van Zijl, and the editorial assistance of Ms Christine Colvin.

The financing of the project by the Water Research Commission and the contributions of the members of the Steering Committee are gratefully acknowledged.

Ideas, assistance and information was received from numerous people in fields related to this project who answered requests for information that appeared in a variety of publications and media. We thank them for taking the trouble to help.

A workshop was held in September at which research priorities were developed. The following individuals attended the workshop at Nylsvley Nature Reserve and contributed to the formulation of the research strategy contained in this report. They are:

Mr JR Vegter,	*Private Groundwater Consultant*
Messrs Hugo Maaren and Tony Reynders,	*Research Managers*, Water Research Commission.
Mr Eberhard Braune,	*Directorate of Geohydrology*, Dept of Water Affairs and Forestry
Mr Brian Rawlins,	*Hydrologist*, University of Zululand
Messrs John Weaver and Reinie Meyer,	*Geo-hydrologists*, CSIR
Mr David Le Maitre,	*Plant ecologist*, CSIR, Stellenbosch
Dr Peter Dye,	*Tree physiologist*, CSIR, Nelspruit
Dr Dave Scott,	*Forest hydrologist*, CSIR, Stellenbosch

TABLE OF CONTENTS

Page

Executive Summary i
Acknowledgements v
List of Tables x
Glossary of Terms xi

1. **INTRODUCTION** 1
   1.1 Background to the project 1
   1.2 Objectives of the project 2
   1.3 The social and economic importance of groundwater in South Africa 2
   1.4 Proposals for a new water law and their implications 3
   1.5 Stages of the Project 3
      1.5.1 *Review of the formal literature* 4
      1.5.2 *Gathering informal literature* 4
      1.5.3 *Multi-disciplinary workshop* 4
      1.5.1 *Report writing* 5
   1.6 Structure of the Report 5

2. **BACKGROUND CONCEPTS** 6
   2.1 The Nature of Groundwater in South Africa 6
   2.2 Groundwater - Surface Water Interactions : Stream Types 6
   2.3 Conceptual Models of the Interactions between Vegetation and Groundwater 9
   2.4 Loss of Groundwater to the Atmosphere 10
   2.5 The Vegetation types of South Africa and their generalised interactions with groundwater 12
      2.5.1 *Biomes of South Africa* 12
         2.5.1.1 Forest biome 12
         2.5.1.2 Thicket biome 12
         2.5.1.3 Savanna biome 13
         2.5.1.4 Grassland biome 13
         2.5.1.5 Nama karoo biome 13
         2.5.1.6 Succulent Karoo biome 14
         2.5.1.7 Fynbos biome 14

3. **LITERATURE REVIEW** 15
   3.1 Influence of vegetation on effective rainfall 15
      3.1.1 *Interception of rainfall by plant canopies* 15
      3.1.2 *Stemflow* 17
      3.1.3 *Throughfall* 18
      3.1.4 *Infiltration* 18

Contents continued ....

3.2 Key Questions 22

3.2.1 *How deeply do plants root, on average and in specialised phreatophytes, and what are the water use rates and physiological characteristics of phreatophytes?* 22

3.2.2.1 Direct observations of the depths of roots systems 22

3.2.1.2 Isotopic evidence for the depths of root systems 23

3.2.1.3 Characteristics of different root systems 26

3.2.1.4 Studies of root systems in Southern Africa 26

3.2.1.5 Summary 27

3.2.2 *What is the impact of a lowering of the water table on obligate phreatophytes? Does the rate at which the water table falls matter?* 28

3.2.2.1 Riparian systems 28

3.2.2.2 Wetlands 31

3.2.2.3 Summary 32

3.2.3 *Can changes in vegetation cover or vegetation management alter the depth and recharge of groundwater?* 32

3.2.3.1 Australia 33

3.2.3.2 Other areas 36

3.2.3.3 South Africa 38

3.2.3.4 Summary 39

3.3 Summary 40

4. **SOUTH AFRICAN CASE STUDIES: SYNOPSIS OF PUBLISHED AND ANECDOTAL INFORMATION** 42

4.1 Vegetation - groundwater interactions in hard rock 42

4.1.1 *The hydrological effects of afforestation* 42

4.1.1.1 Deep rooting by eucalypts 42

4.1.1.2 The geohydrology of a wattle plantation 43

4.1.2 *Bush clearing in North West and Northern Provinces* 44

4.1.3 *De Aar's Water Supply: possible impacts on the productivity of adjacent agricultural land* 44

4.1.4 *Kathu Impact Study: Kathu Forest, near Sishen, Northern Cape Province* 44

4.1.5 *Miscellaneous observations in Northern KwaZulu-Natal* 45

4.1.6 *Grootgeluk Coal Mine, near Ellisras, NW Province* 45

4.1.7 *Mr Koos Viviers (Geohydrologist with Eskom Mining)* 45

4.1.8 *WT (Jack) Bennett, Bennett Drilling, Pretoria* 46

4.1.9 *Richmond Karoo, "Karoo word droog gepomp"* 46

4.2 Vegetation - groundwater interactions on coastal aquifers 46

4.2.1 *Rising water tables and poor drainage on Cape Flats township developments* 46

4.2.2 *Timber Plantations on the Zululand coastal plain* 47

4.2.3 *Atlantis Aquifer* 47

4.2.4 *Blouvlei* 48

4.2.5 *Miscellaneous observations* 48

Contents continued ....

	4.3	Vegetation - groundwater interactions on Kalahari sands		48
		4.3.1	*The observations of Dr Chris Jennings*	48
	4.4	Vegetation - groundwater interactions on alluvial aquifers		49
		4.4.1	*Venetia Diamond Mine on the Limpopo: monitored exploitation scheme*	49
		4.4.2	*Limpopo River and Irrigation Demand*	50
		4.4.3	*Water Supply to Rehoboth: The effects of the Oanob Dam on the Oanob River on the health/survival of the riparian Woodland downstream of the dam*	50
		4.4.4	*Kuiseb River in Southern Namibia*	50
		4.4.5	*Buffels River, Northern Cape Province: Okiep Copper Mine*	51
	4.5	Geo-technical issues related to vegetation		51
		4.5.1	*Lethabo Power Station and other Highveld construction sites*	51
		4.5.2	*Pilkington Glass Factory, Springs*	52
	4.6	Mortality of trees due to changes in hydrogeology		52
		4.6.1	*'Anabome' National Monument, Potgietersrust*	52
	4.7	Vegetation and mine water		53
	4.8	Wetlands and riparian corridors		53
		4.8.1	*Wetlands*	53
		4.8.2	*Riparian corridors*	54
5.	**CLASSIFICATION OF VEGETATION - GROUNDWATER INTERACTIONS**			56
	5.1	Elements of a classification		56
	5.2	A groundwater viewpoint		57
6.	**RESEARCH ISSUES AND PRIORITIES**			59
	6.1	The need of research		59
		6.1.1	*Support for broad-scale policy and planning relating to groundwater resources*	60
		6.1.2	*Increasing general awareness*	61
	6.2	Research fields		61
		6.2.1	*Identification of Groundwater Dependent Ecosystems*	61
		6.2.2	*Assess the effects of groundwater abstraction on vegetation*	61
		6.2.3	*Assess the effects of changing vegetation cover and condition on groundwater*	63
		6.2.4	*Quantitative modelling of groundwater-vegetation interactions*	63
		6.2.5	*Mapping of biohydrogeological response units and identification of "hot-spots"*	64
	6.3	Other Issues		65
		6.3.1	*Evaluation of the present groundwater monitoring programme*	65
		6.3.2	*Capacity Building*	65
	6.4	Summary of research requirements		65
7.	**BIBLIOGRAPHY**			67
	APPENDIX : PROCEEDINGS OF A WORKSHOP			

LIST OF TABLES

Table 3.1: Examples of ranges in interception per rain-day for different vegetation types in South Africa (after Schulze 1981).

Table 3.2: Redistribution of gross rainfall into different components, for individual trees or for the woody vegetation as a whole, in relation to climate, rainfall intensity and woody species. After Breman & Kessler (1995).

Table 3.3: Relative water infiltration rates in relation to soil texture and presence of a woody canopy, from studies in semi-arid regions. After Breman & Kessler (1995).

Table 3.4: Run-off and leaching beyond 1.80 m soil depth at three sites with sandy-loam soils, in West Africa (Roose 1981; in Breman & Kessler 1995).

Table 3.5: Characteristics of root systems of woody species occurring in the Sahelian and Sudanian zones of West Africa, including indication of the root system type. 1 = deep roots and few superficial roots; 2 = deep roots and many superficial branch roots; 3 = shallow and extending roots. After Breman & Kessler (1995).

Table 3.6: Transpiration losses by some woody species in the Sahelian and Sudanian zones of West Africa during the dry season. After Breman & Kessler (1995).

Table 3.7: Comparative rates of recharge under different vegetation types and following vegetation changes in the winter rainfall regions of Western and south-eastern Australia and the summer rainfall region in eastern Australia. spha = stems per hectare

Table 3.8: A comparison of the impacts of different vegetation types on evaporation, runoff and recharge (after Carlson *et al.* 1990).

Table 3.9: Evapotranspiration from different stages of central OFS grassland based on lysimeters (Snyman 1988).

Table 3.10: The maximum effects of various processes associated with woody plants in the Sahel and Sudan zones on water availability for primary production of a mixed vegetation, considering the effects in the canopy area and canopy cover in the vegetation as in the pre-drought situation, in comparison to a vegetation without woody plants. After Breman & Kessler (1995).

Table 6.1: Summary of information on vegetation-groundwater interactions in Southern Africa and indication of priority research needs.

GLOSSARY OF TECHNICAL TERMS

Words and phrases in italics are defined in this section. Symbols in common use are included.

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

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

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.

Aquifer - a saturated stratum which contains intergranular interstices, or a fissure / fracture or a system of interconnected fissures / fractures capable of transmitting groundwater rapidly enough to supply a borehole or spring directly. The fissures / fractures are generally bound either by aquitards / acquicludes or by aquifuges. An unconfined aquifer is one where the *water table* forms the upper surface. This definition is proposed instead of those appearing in hydrogeological handbooks which are based on the concept of intergranular porosity and permeability only. Aquifers in hard rock formations consist of either single fissures / fractures or of two-dimensional sets of closely spaced parallel fissures / fractures or three-dimensional networks of interconnected fractures / fissures.

Aquifuge - a body of rock which contains no interconnected openings and therefore neither absorbs nor transmits water.

Aquitard / aquiclude - a saturated body of poorly permeable rock that is capable of slowly absorbing water from and releasing it to an aquifer. It does not transmit water rapidly enough by itself, to directly supply a borehole or spring. A body of compact fresh hard rock is an aquifuge. Water-bearing fractures / fissures which may be contained in such rock bodies, are the aquifer(s). Decomposed hard rocks on the other hand contain intergranular interstices. As the decomposition products generally are clayey, bodies of saturated decomposed rock usually are aquitards rather than aquifers. Saturated alluvial deposits normally consist of both stratified Aquitard and aquifer materials.

Baseflow - the water in the stream when at its minimum or base level of flow; this the level to which the stream flow returns between storms; in climates with seasonal rainfall it is often treated as the dry season flow; it is derived from soil water drainage and groundwater; generally synonymous with the term low flow.

Baseflow recession - the rate at which the increased streamflow following rain returns to the baseflow levels after the flow has peaked.

Biome - a group of similar types of communities characterized by their distinctive plant types, e.g. tropical rain forest, savanna

Capillary zone or fringe - lies immediately above the saturated zone (the level where the pressure head is zero) and is also saturated; more accurately called the tension-saturated zone because the water is held in the soil pores against gravity by capillary tension.

Catchment - synonymous with a river basin; though in South Africa the term *mountain catchment* is often used to describe the upper water producing portions of a river drainage.

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

Deep seepage - the loss of water from a catchment which is not measured at a gauging weir; it occurs where there are routes for water movement through the underlying geological formations or where a subsurface divide does not coincide with a surface divide.

Disconnected stream - not a formal term; a situation when a stream is above and not in hydrological contact with local groundwater.

Drawdown - the difference between the water level observed during abstraction and the rest water level.

Ecotone - a transition zone; a region of overlapping plant associations, as that between two biomes or two adjacent ecosystems.

Effective rainfall - see net rainfall.

Effluent stream - a stream which is fed directly by the surrounding groundwater : the piezometric level is above the stream surface and discharge to the surface feeds the stream. See Influent stream and Disconnected stream.

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 transition of water from the liquid phase to the vapour phase. It is also expressed in units of depth to relate it to rainfall. During this process energy (termed latent heat) is absorbed. Symbol E or Et. It includes vapour from all sources; interception, transpiration, evaporation from soil and open water.

Evapotranspiration - in modern usage is replaced by the term evaporation - the total loss of water in vapour form from open water, from the plant surface (interception), through plants (transpiration) and from the soil surface. Symbol usually E_t or E_a. [Now considered redundant : the term evaporation is preferred.]

Fynbos - the sclerophyllous vegetation that is native to the western and southern Cape regions of South Africa.

Geophyte- plants with meristematic portions (buds or organs) located on the plant below the soil surface, as on bulbs or rhizomes.

Grassveld - grassland, range

Groundwater - the use of this term should be restricted to water in the zone of saturation. It flows into boreholes / wells, emerges as springs, seeps out in streambeds or elsewhere in surface catchments and is not bound to rock (particle) surfaces by forces of adhesion and cohesion. Water contained in *aquifers*. Some, misleadingly, include all subsurface water under groundwater.

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

Groundwater discharge - the release, or emergence of *groundwater* from an *aquifer* into the unsaturated soil and/or into surface water. Discharge areas occur in the lower parts of catchments and may comprise springs or seeps, where groundwater contributes to the surface runoff or streamflow. These areas are synonymous with the source areas of rivers.

Herbaceous plant - a plant having the characteristics of a herb; having the texture of colour of a foliage leaf.

Hydraulic conductivity - a measure of the ability of a material (here soil and rocks) to transmit water under the influence of gravity and hydraulic forces. (Loosely synonymous with *permeability*)

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

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

Influent stream - a stream that is 'perched' above the surrounding groundwater to which it is connected and is feeding; i.e. a form of direct recharge of groundwater.

Interception - the capture of precipitation and its subsequent loss by evaporation on surfaces on which it lands (e.g. leaves, bark, vegetation, litter, etc.) Symbol I and sometimes E_i

Interflow - refers to the rapid lateral movement of subsurface water from rainfall through the soil layer; generally synonymous with *subsurface stormflow*.

Leaf-area index - the leaf-area index is measured as the surface area of the leaves per unit area of ground e.g. a leaf-area index of 2.0 means there area 2 m^2 of leaf per m^2 of ground. The leaf area is normally measured on the one (upper) side only for flat leaves but the methodology may vary.

Legume - any member of the pea family (Fabaceae) e.g. beans, peanuts and alfalfa.

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

Macropore flow - the movement of water through the *unsaturated* and *saturated* zones in relatively large gaps or channels in the soil and regolith. These include desiccation cracks, fissures and root channels. Flow rates are usually significantly more rapid than *matrix flow*.

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

Moisture stress -a measure of the moisture shortage in the plants tissues and thus of the tension in the water conducting tissues (xylem) in the plant. It is usually measured in units of pressure (mega Pascals or MPa).

Net rainfall - or net precipitation, is usually taken as total rainfall less interception (on the sum of throughfall and stemflow in forests.)

Overland flow - strictly speaking this refers to the movement of water from rainfall over an impervious (e.g. rock) or saturated surface; the water does not enter the subsurface at any point; in practice it is often used loosely to include all *surface runoff* which may also come from water which has infiltrated the soil. Also called Hortonian flow.

Perched groundwater - unconfined groundwater separated from an underlying main body of groundwater by an unsaturated zone. (A.G.I. glossary)

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

Percolation - in Soil physics, it is defined as the process by which the water moves through the soil and under-lying material under the influence of gravity and hydraulic forces. In Geohydrology, the therm is confined to flow in the zone of saturation.

Perennial - a plant which lives for more than two years; herbaceous perennials have stems and/or leaves which are produced and die back annually, with their underground stems and/or roots remaining alive; woody perennials, e.g. trees and shrubs, have aerial stems which may live for many years.

Permeability - a measure of the ability of a material (here soil and rocks) to transmit water under the influence of gravity and hydraulic forces. (Synonymous with *Hydraulic conductivity*)

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

Phreatophytes - plants that habitually obtain their water supply from the *saturated zone*, either directly or through the capillary fringe. Obligate phreatophytes are 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.

Plumule- the first bud of an embryo, the part of the embryonic axis above the cotyledonary node.

Pioneer - plant species or community that typically is the first to occupy a site after disturbance or clearing, e.g. after fire or cultivation.

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

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

Preferential flow -equivalent to macropore flow.

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

Primary openings - Interstices that were formed contemporaneously with the formation of the sedimentary deposit or rock that contains them. Synonymous with primary porosity. Forms primary *permeability*.

Quickflow - that portion of stormflow (storm runoff) that, by convention, is not base flow (groundwater discharge).

Recharge - see groundwater recharge.

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

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

Riparian - growing by rivers or streams.

Roots - tap, sinker, lateral, etc. - the descending axis of a plant, normally below ground; functions include anchorage, absorption and conduction of water and minerals, and sometimes food storage; roots lack nodes and internodes.

Runoff - all the surface and subsurface flow of water from a *catchment*; usually used to refer to the (amount) of water that leaves a catchment in a period of time. As most catchments are assumed to have no subsurface flow at the measuring point it is generally equivalent to the surface runoff. All forms of runoff are measured in units of volume (m^3 or ft^3) but are sometimes expressed in units of depth (see rainfall equivalents). Common symbol is Q.

Saprolite - *In situ* thoroughly decomposed rock.

Saturated zone - commonly defined as the portion of the profile below the *water table* or where the soil pores are saturated with water; more accurately defined as the level at which the pressure head is zero and which thus excludes the *capillary fringe*.

Savanna - a grassland with scattered trees or scattered clumps of trees, that experiences a characteristic long, dry season.

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

Secondary openings - Interstices that were formed by processes that affected the rocks after they were formed. Synonymous with secondary porosity. Forms secondary *permeability*.

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

Soil evaporation - the loss of water in vapour form from the surface of the mineral soil.

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

Soil porosity - the fraction of the total soil volume which is pore space.

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

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

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

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

Stemflow - the intercepted water that runs down the branches and stem of the plant.

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

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

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

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

Succulent - A plant which accumulates water in fleshy, water-storing stems, leaves or roots.

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

Throughfall - the rainfall that passes right through or drips from the plant canopy.

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

Unconfined aquifer - see aquifer.

Understorey - the trees in a forest found beneath the level of the main canopy.

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

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

Vapour pressure deficit - a measure of the water absorption capacity of the air based on the difference between the partial pressure of water vapour if the air were saturated and the ambient water vapour pressure. It is usually calculated from the relative humidity and temperature of the air and in units of

Pascals (Pa).

Water table - the upper surface of the zone of *saturation* of an *unconfined aquifer*. On this surface the hydrostatic pressure is equal to atmospheric pressure (this therefore excludes the capillary fringe).

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

Wetland - plant community or site with a soil that is flooded for sufficiently long periods for waterlogging to become the dominant factor determining its diagnostic characteristics.

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

Xerophyte - a plant that is adapted to dry or arid habitats.

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

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

Zone of saturation - see phreatic zone.

1. INTRODUCTION

1.1 Background to the project

This research project was prompted by several factors:

- The limited nature of water resources in South Africa and the current review of water law have focussed attention on the reality that surface and groundwater are not separate entities: water used in one form or from one source will reduce the availability of water elsewhere. The separation of surface and groundwater has been convenient in the past but is artificial. We need to have a better understanding of how these two phases of water interact for purposes of planning and management of water resources.

  The separation of surface and groundwater hydrology into different scientific disciplines has also influenced research programmes in South Africa. A survey of the proposed research programmes and the problems and issues relating to inland water ecosystems shows that groundwater is rarely even mentioned. For example, Noble & Hemens (1978) in a review of research needs of inland water ecosystems, recognise hydrological research, including groundwater, as vital but place it in a brief section on related research outside their research programme. Groundwater is implicit in many of the problems and issues discussed in reports describing river (Ferrar *et al.* 1988) and wetlands (Walmsley 1988) research programmes, but it is not discussed explicitly. The study of the Pongolo floodplain (Heeg & Breen 1982), the synthesis of information on river conservation (O'Keeffe 1986) and the analysis of ecological flow requirements of rivers (Ferrar 1989) do little more than note that groundwater is important and that manipulations of surface water resources can influence groundwater dynamics. The more recent compilations and syntheses on river ecosystems (Davies *et al.* 1993) and wetlands (Cowan 1995) add very little more as they focus primarily on surface waters and surface water driven processes.

- A recent study on recharge in South Africa (Bredenkamp *et al.* 1995) points to the complexity of the recharge processes and the need for well-planned process studies at the plant-soil-aquifer interface.

- There is a scattered body of evidence, much of it anecdotal, on plant-soil-aquifer interactions in South Africa. There is evidence, for instance, of land-use changes affecting groundwater levels (Rawlins and Kelbe 1991) and suggestions have been made by farmers that groundwater exploitation is having a detrimental effect on karoo veld productivity (LWSK 1989). A need exists to draw this information in its various forms and from a broad range of sources together, and to assess it scientifically.

- Internationally, more work has been done on this topic and this source would provide a useful adjunct to local information, and serve as a starting point in the development of a theoretical basis for understanding the local situation.

- Locally, there is a need to collate and assess what is known of plant-soil-aquifer interactions. Specifically, to assess the geographical extent and the amount of water that is involved. In order to build a scientific basis for our understanding we require hypotheses for the process of interaction between ecosystems and groundwater.

1.2 Objectives of the project

The objectives of the research programme were as follows:

- Explore the scope of this subject area, by gathering evidence from the published literature and gathering evidence from South African experience.

- Outline the potential impacts of vegetation on groundwater recharge, and the potential impacts of groundwater abstraction on vegetation well-being, at the landscape to regional scale.

- Develop hypotheses as a theoretical basis for understanding the processes of vegetation-groundwater interactions for different climatic, geomorphological and vegetation types in South Africa.

- Convene a national workshop of a cross-section of relevant experts from various disciplines to establish the status of our knowledge, classify vegetation-groundwater situations, and prioritise research topics.

- Produce a research strategy for relevant issues in this inter-disciplinary research area.

At the initiation of the project it was decided that all forms of interactions (real and perceived) between vegetation and groundwater would be studied; that no limits would be placed on the scope of the project in this regard.

1.3 The social and economic importance of groundwater in South Africa

Roughly 13% of all water used in South Africa is drawn directly from groundwater (DWAF 1986). While this is not a particularly large proportion, groundwater is the sole or primary water resource in the more arid two-thirds of the country and is the primary source of water for approximately 280 towns and several major irrigation systems (Vegter 1995). To take a broader perspective of groundwater though, most of the remainder of rural South Africa, and especially the rural poor, are dependent on run-of-river water or springs for their domestic and livestock watering needs. Both springs and the dry season base flow (low flow) of rivers are direct discharges of groundwater, and the strength of supply is dependent on the levels of groundwater storage. Hence, groundwater is important for virtually all rural South Africa; a much larger area that previously accepted.

1.4 Proposals for a new water law and their implications

South Africa's water law is now under review is holistic in its principles and approaches to water resources management. Water resources are seen as indivisible, with the National Government as its custodian to ensure that development, apportionment, management and use of the resources are carried out using the criteria of public interest, sustainability, equity and efficiency of use (Department of Water Affairs and Forestry 1997; Braune and Dziembowski 1997). This has major implications for a more integrated management of all waters, quantity and quality, on the surface and underground.

Five of the more pertinent of the principles behind the new water law are quoted in full to emphasise their significance to the relevance of this report (DWAF 1997)

Principle 2
All water, wherever it occurs in the water cycle, is a resource common to all, the use of which shall be subject to national control. All water shall have a consistent status in law, irrespective of where it occurs.

Principle 5
In a relatively arid country such as South Africa, it is necessary to recognise the unity of the water cycle and the interdependence of its elements, where evaporation, clouds and rainfall are linked to groundwater, rivers, lakes, wetlands and the sea, and where the basic hydrological unit is the catchment.

Principle 7
The objective of managing the quantity, quality and reliability of the nation's water resources is to achieve optimum, long term, environmentally sustainable social and economic benefit for society from their use.

Principle 8
The water required to ensure that all people have access to sufficient water shall be reserved.

Principle 9
The quantity, quality and reliability of water required to maintain the ecological functions on which humans depend shall be reserved so that the human use of water does not individually or cumulatively compromise the long term sustainability of aquatic and associated ecosystems."

These principles have many implications for water use, and for administrators charged with regulating use. The application of these principles implies a knowledge of hydrological cycling and interactions between water and environment that we do not yet have, or which we have in limited areas only. The need will therefore become ever more pressing to improve our understanding and prediction of how water use in one phase or physical location can affect the availability of water in another phase or location, or the environment. Many of these gaps in our understanding concern groundwater and its relationship to vegetation. So, for example, we shall have to possess a quantitative understanding of how exploitation of an aquifer in one area affects the riparian ecosystems, both aquatic and terrestrial, at some perhaps distant location, where that aquifer discharges. Specifically, it is necessary that we understand:

(i) the dependence of vegetation on groundwater, and the dynamics of such dependancies, and the significance of the dependent vegetation types, and

(ii) the influence of changes in vegetation type and condition on hydrological cycling and catchment water balance, in particular the groundwater resources.

1.5 Stages of the Project

1.5.1 *Review of the formal literature*

A Waterlit search was conducted and personal reference collections were used to gather published information relating to the subject. Another important source was internal reports of the Directorate Geohydrology of the Department of Water Affairs and Forestry.

1.5.2 *Gathering informal information*

In an attempt to tap unpublished material and anecdotal information, requests were sent to interest- group sites on the Internet, and published in the:

- Borehole Water Journal
- the Bulletin of the South African Institute of Ecologists and Environmental Scientists
- the newsletter of the Ground Water Division of the Geological Society of South Africa
- S.A. Water Bulletin (WRC)
- Landbounuus/Agricultural News (newsletter and radio programme)

Also, personal contact was established with individuals to find out details of specific situations where vegetation and groundwater interact.

1.5.3 *Multi-disciplinary workshop*

In September 1996 a 2-day workshop was held at Nylsvley Nature Reserve at which a group of interested scientists of various disciplines shared their insights of specific South African cases involving interactions between vegetation and groundwater; debated and proposed various classification of vegetation-groundwater interactions; and proposed research topics and priorities for this subject area in South Africa. The proceedings of this workshop are included in the body of the report where appropriate. The record of the workshop programme and activities are given as Appendix 1.

1.5.4 *Report writing*

The final stage of the project has been to summarize and draw together the various pieces of information that have been gathered, organize the information and prepare the research priorities list.

1.6 Structure of the Report

The report begins with an outline of the basic processes that affect the interaction between vegetation and groundwater. At this stage we try to highlight and introduce the terminology of the field. This serves as an introduction to a structured literature review (Part 2). This is followed by an extensive literature review (Section 3), and a review of anecdotal and more formal information from Southern African experience (Section 4). The report concludes with a listing of research needs and priorities, based on the gathered information and workshops. There is an extensive list of references and the record of a workshop is included as an appendix.7

2. BACKGROUND CONCEPTS

2.1 The Nature of Groundwater in South Africa (Vegter, 1995)

Over about 90% of the surface of South Africa, groundwater occurs in secondary aquifers in so-called hard rocks. These igneous, metamorphic and sedimentary rocks, ranging in age from Swazian to Jurassic lack primary interstices to act as primary aquifers. Secondary aquifers in South Africa include the following:

- Groundwater contained in fractures (faults and joints) in hard rocks and to some extent pores in the weathered zone (saprolite) of these rocks.
- Groundwater in dolomite and limestone contained in fissures and larger dissolution openings as well as intergranular interstices in the insoluble residue and younger deposits filling dissolution openings.
- Groundwater occurs in localised cells rather than extensive regional aquifers, with the exception of dolomite areas which have been compartmentalized by dykes into groundwater units of up to 100's km^2 in extent.

Over the remainder of the country groundwater occurs in three different types of primary aquifers, namely:-

- Narrow, discontinuous strips of alluvium along some rivers. These are important aquifers but of very limited and local extent, e.g. Limpopo, and Buffels Rivers.
- Recent (Cainozoic) sand deposits fringing the coasts, e.g. Northern Zululand, Cape Flats and Atlantis.
- The extensive Kalahari sand deposits of Tertiary Age, forming important primary aquifers particularly where pre-Kalahari Valleys have been filled.

2.2 Groundwater - Surface Water Interactions : Stream Types

Three main types may be distinguished (Vegter and Pitman, 1996):

1. *Piezometric surface at all times below streambed level* - characteristic of ephemeral streams, though not necessarily limited to them only. One of two conditions may obtain.

a) Material between streambed and piezometric surface is pervious - the stream is *influent* or *losing* and the piezometric surface slopes downward away from the stream (illustrated in Figure 1.1). The stream acts as a sink and recharges groundwater. Little or no work has been undertaken in South Africa to quantify stream recharge.

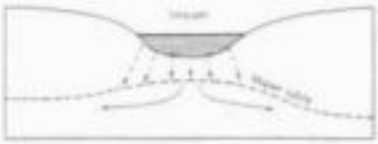

Figure 1.1

b) Intervening material more or less impervious - very little or no recharge takes place - i.e. a *detached* stream.

In the opinion of Vegter and Pitman (1996) conditions over much of the country militate against rivers being all but minor localised sources of recharge for the following reasons:

- the hard-rock environment and dearth of laterally extensive alluvial deposits below river bed level;
- the fact that the watertable is a subdued replica of the topography over the greater part of South Africa inhibits the lateral expansion of the recharge mound that is being built up below the river by infiltrating water and,
- rocky river beds and silty channels that limit flow of water out of the channel.

2. *Piezometric surface slopes laterally down towards the stream.* One of the following conditions may be encountered:

a) Groundwater reaches and emerges into the stream at all times - *an effluent or gaining stream*. The piezometric surface at the stream is permanently above the stream stage and the material between it and the streambed us pervious - porous or fractured. The stream acts as a drain is effluent and perennial (illustrated in Figure 1.2).

Figure 1.2

b) Groundwater from the catchment area emerges into the stream at intervals and i.e. for a while after recharge episodes - the steam is *intermittent* or *ephemeral*. During dry periods groundwater storage is depleted by the effluent seepage or in combination with evapotranspiration from the stream banks and within the catchment. Groundwater may be replenished to a certain extent in the immediate vicinity of the stream by storm runoff - termed *bank storage*.

c) Ground water does not reach the stream because it is permanently being dissipated along its flow path towards the stream by evapotranspiration - a *famished* stream (author's terminology).

3. The piezometric level fluctuates alternately above and below the stream stage

The stream is underlain and bordered by alluvial deposits and / or porous decomposed rock. The stream is alternately in- and effluent (illustrated in Figure 1.3).

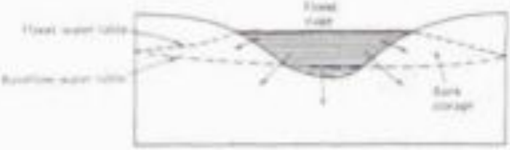

Figure 1.3

A particular designation does not necessarily apply to the full length of a stream. Most rivers exhibit different characteristics along different reaches. A good but somewhat extraordinary example is that of the Wonderfontein Spruit on the far West Rand which is influent and disappears along certain stretches and effluent along others where fed by spring flow.

Examples of river types in South Africa (Vegter and Pitman, 1996):-

Influent	Kuruman River downstream from at least Frylinckspan Molopo River downstream from at least Tshidilamolomo Phepane, Kgokgole, and other "laagtes" in the catchments of the Kuruman and Molopo River
Detached	Relatively steeply graded and dry, rocky stream beds particularly in the arid northwestern parts of the country

Effluent	Upper reaches of perennial rivers, e.g. those rising on the eastern escarpment such as the Vaal, Olifants (Gauteng), Tugela, Blyde, Komati etc.
Intermittent	Streams in the Karoo such as the upper reaches of the Salt River (Beaufort West), the Kamdeboo, the Sundays, the Brak (De Aar)
Famished	Rocky sections of the Limpopo River such as alluvium-free stretches between Stockpoort 1 LQ and Sannandale 9 LQ; and the steeper graded section between the junctions with the Lephalala and Motlouse Rivers. The bordering country which is underlain by granulite-gneiss of the Limpopo Mobile Belt is very poorly endowed with groundwater
In-/effluent	Wide stretches of relatively unexploited alluvium along the Limpopo River between the confluence of the Marico and Crocodile Rivers and its junction with Mahalapswe River. Under conditions of heavy exploitation, as is presumably the case downstream along the Limpopo at Weipie and along the Crocodile River between Koedoeskop and Thabazimbi, the stream may change its dual character to influent only.

2.3 Components of Interactions between Vegetation and Groundwater

The focus of this report is on how groundwater resources and their utilisation are affected by or have an effect on vegetation (Figure 2.1). Groundwater-vegetation interactions can be considered from two aspects:

(a) the effects of vegetation on groundwater recharge and extraction of groundwater by vegetation

(b) the effects that abstraction of groundwater may have on vegetation communities (or, to put it more broadly, terrestrial habitats) the character of which is determined to some extent by groundwater.

The two aspects cannot be completely separated. For example the extraction of water from the soil profile by roots reduces water flux to groundwater. Manipulation of vegetation cover by altering density or species changes water-use, infiltration and soil evaporation and thus ultimately influence the amounts and patterns of surface runoff and groundwater recharge. Figure 2.1 illustrates some of the more typical interactions between vegetation and groundwater.

Vegetation redistributes water from rainfall through interception, throughfall and stemflow. Once the rainfall reaches the soil, the amount and rate of water entry into and through the soil is determined by factors such as soil physical properties (e.g. porosity), soil depth, surface storage capacity, soil moisture deficit and the slope of the surface (some of which characteristics may in turn be affected by vegetation). In the soil profile and regolith water percolation is controlled by soil texture and changes in texture and the presence of macropores which allow rapid fluxes of water through the unsaturated zone.

The ability of vegetation to tap groundwater (i.e. from the saturated zone) depends on the depth to the water table, the penetrability of the profile and the inherent ability of the plant species to develop deep root systems. Plants also extract water from the unsaturated zone, increasing the available water storage capacity of the profile and thus also reducing recharge.

Abstraction of groundwater may affect vegetation that is reliant on that groundwater body, for example, where it occurs near the ground surface and is directly tapped by plants, or where it discharges in wetlands, springs, streams or rivers.

2.4 Loss of Groundwater to the Atmosphere

Below a certain depth groundwater will be virtually cut off from the surface unless a connection is provided by roots. Even with roots to groundwater, there are physical limits to how deep plants can extract water. This brief section attempts to outline the limits for upward movement of water from the saturated zone.

The capillary zone is a saturated band above a water table where water is held by capillary forces against gravity. The thickness of the capillary zone is determined by the soil texture and other characteristics. The very small pores in clay soils may support a capillary fringe of 1.5 m, but in coarser material capillarity is reduced such that the saturated zone in medium textured sands would be around 0.4 m. Above the capillary zone, unsaturated upward water movement is driven by matric suction, up to the point where this is equal to gravitational forces; to an approximate maximum of 3 m above the water table in clay. Above this water movement would need be in the form of vapour diffusion. This flux would be small because of large "resistances" to vapour movement. Hence, where water tables are below 3 m upward water fluxes driven by evaporation would be minimal. Except where water tables are shallow therefore or recharge very low, the primary loss of groundwater would have to be through root extraction or groundwater discharge.

Water extraction by plants is driven by the very low water potentials in the atmosphere around the plant canopy, which under hot dry weather could theoretically lift water a full 150 m. This height is based on a generally accepted permanent wilting point of -1.5 MPa in plants, though most South African plants only wilt at -2.0 to -3.0 Mpa (Scholes, pers. comm., 1996[1]). Thus extraction of water by roots is not practically constrained by atmospheric demand, but rather by the nature of the plant, physical obstructions in the soil, e.g. impenetrable layers, and the costs to the plant of rooting to great depths (given that deep penetration is possible).

[1]. Dr RJ Scholes, CSIR, Pretoria

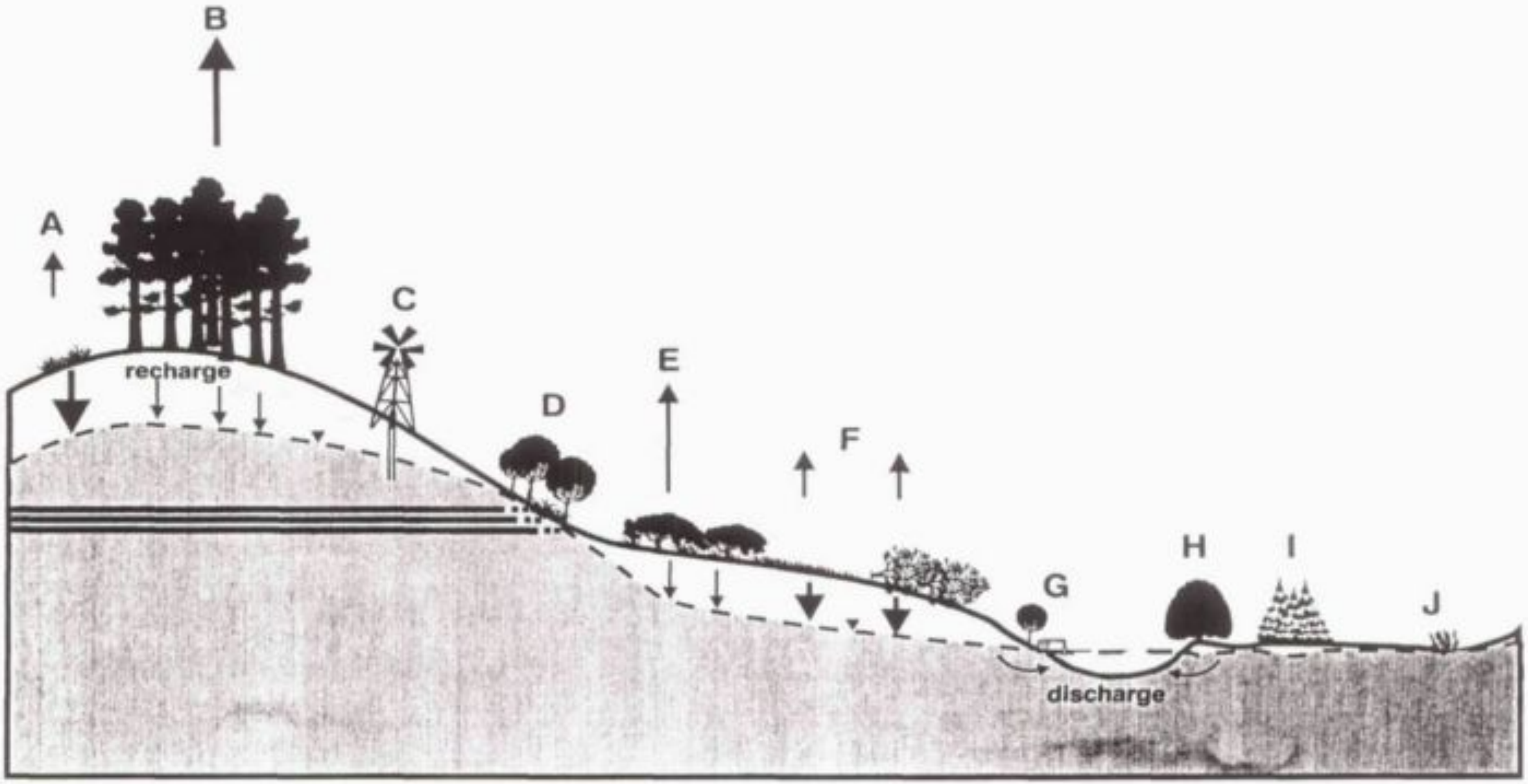

Figure 2.1: Schematic diagram illustrating some typical interactions between vegetation and groundwater.

2.5 The Vegetation types of South Africa and their generalised interactions with groundwater

The aim of this section is to provide a very generalised overview of the kinds of vegetation found in South Africa and their likely interactions with groundwater based on the rooting behaviour of the dominant plant forms. As will be shown in the literature review, the primary interactions of plants with groundwater are through transpiration and, to a lesser extent, interception. Transpiration losses from groundwater occur primarily from the unsaturated zone and from shallow alluvial and coastal aquifers, but deep root systems can enable plants to tap groundwater at great depths.

2.5.1 *Biomes of South Africa*

The best known vegetation map of South Africa is the one produced by Acocks (Acocks, 1953). The veld types mapped by Acocks were based on their similar agricultural potential. While agricultural potential is related to ecological characteristics the relationships are not always direct. There is now a new map of the vegetation of South Africa which is based on ecological and structural similarities (Low and Rebelo, 1996).

This new classification recognises a total of 68 different vegetation types grouped into seven different biomes. [A biome is a natural grouping of vegetation according to the life-form of the dominant plants and ecological similarities (Rutherford & Westfall, 1986).] The seven biomes are: forest, thicket, savanna, grassland, nama karoo (summer rainfall), succulent karoo (winter rainfall) and fynbos (including renosterveld on shales). The descriptions of biomes are based on Low and Rebelo (1996, unless otherwise indicated). Information on groundwater is taken from Vegter (1995) and associated groundwater maps.

2.5.1.1 Forest biome

Forests are restricted to frost-free areas with a mean annual rainfall of >525 mm (winter rainfall) to >725 mm (summer rainfall) and are found from sea-level to 2 100 m altitude. Forest vegetation only covers 0.6% of South Africa. Afromontane forest is found in the Cape mountains, southern Cape coastal plateaux and along the escarpment. Coastal forest is found on calcareous dune sands from Port Elizabeth northwards. Sand forest is found on the deep sands of the Zululand coastal plains.

Interactions with groundwater are likely to be important in coastal and sand forest where access to groundwater under the dune may be important for deep-rooted trees.

2.5.1.2 Thicket biome

Thicket is a sub-tropical vegetation which varies from a low shrubland to low forest and is found in a wide range of habitats. Thicket covers 3.3% of South Africa. It is most widespread from the Little Karoo east and northwards along the coastal belt where it is found in the dry and hot river valleys up to northern KwaZulu-Natal. Dominant species vary from succulents (e.g. spekboom) to woody species but both are always present.

Groundwater interactions are probably limited to riparian situations although many of the shrubs and trees are likely to be able to develop deep root systems where rocks are deeply weathered or fractured. Dune thicket species may have roots down to the water tables.

2.5.1.3 Savanna biome

This biome is characterised by a grass layer and a distinct upper layer of woody plants and covers 33.7% of the country. Savanna occurs in a wide variety of situations from sea level to 2 000 m and from 235-1 000 mm of rainfall per year. Soils range from rocky and shallow to deep Kalahari sands.

There is a divergence of opinion on the rooting behaviour of savanna trees and shrubs and thus the importance of vegetation groundwater interactions. Some believe that root systems only penetrate as deeply as the typical wetting depth of the summer rains with grass roots dominant in the upper soil and trees in the deeper layers. Many species have extensive lateral roots which can also produce sinker roots. Root and isotope studies show that woody plant root systems often access unsaturated layers or groundwater at substantial depths (+10 m) where the profile permits root growth. Certainly vegetation groundwater interactions are important in the riparian communities, especially forests, in this biome and these communities are sensitive to lowering, or raising of water tables.

2.5.1.4 Grassland biome

The dominant life form is formerly grasses and woody plants are confined to certain habitats (e.g. rocky areas, riparian strips). Grasslands cover 26.4% of South Africa over a wide range of annual rainfall, but now at least half are under cultivation. Grass roots are generally confined to the upper 0.5-1.0 m of the soil but can penetrate to 3 m or more.

Interactions with groundwater will be limited to reducing recharge by interception and moisture uptake from the unsaturated zone, except in discharge areas such as wetlands and riparian strips.

2.5.1.5 Nama karoo biome

The dominant vegetation is a mixture of grasses and low shrubs. Its distribution is primarily determined by the occurrence of summer rainfall varying from 100-520 mm per year. Soils are typically shallow over rock with deeper soils being confined to the lower slopes of koppies and valley bottoms. Many of the shrubs are drought deciduous and most appear to be able to develop deep root systems where roots can penetrate the profile.

Interactions with groundwater are likely to be important in alluvial plains and riparian situations where the plants can reach, and are probably dependant on the limited groundwater. The ability of exotic *Prosopis* species (moderately drought-tolerant, facultative phreatophytes) to form extensive thickets in these situations suggests that groundwater is available. *Prosopis* seedling recruitment is apparently also linked to wet periods when water tables are high (or profiles well wetted) and seedling root systems can establish and maintain contact with the capillary fringe.

Establishment of *Acacia karoo* also requires similar conditions (Barnes *et al.* 1996).

2.5.1.6 Succulent Karoo biome

This is found in the winter rainfall region with a rainfall of 20-290 mm per year and very dry summers. It covers 6.5% of South Africa. The vegetation is dominated by succulent perennial shrubs and is renowned for the abundance of spring flowering annuals and geophytes. Non-succulent woody plants are sparse except along the larger rivers.

Interactions with groundwater are probably very limited and confined to riparian situations as in savanna.

2.5.1.7 Fynbos biome

The vegetation communities of the fynbos biome (6.1% of South Africa) are generally dominated by shrub species and can be split into two major groups: fynbos on the infertile soils derived from the Cape Supergroup Sandstones and more fertile Cape Granite Suite, and Renosterveld on the shales of the Malmesbury and Bokkeveld groups and Karoo Sequence, occurs in areas with 250-600 mm of rainfall with at least 30% falling in winter; most of the renosterveld has been converted to wheatlands and other crops.

Most renosterveld shrubs are likely to develop deep roots where possible but because groundwater resources are very limited in the shales, interactions with groundwater are likely to be minimal. The same situation occurs in most fynbos areas but groundwater interactions may be important on the Quaternary sands on the western, southern and south-eastern coasts and the limestones and laterites of the Agulhas-Riversdale coastal plain.

3. LITERATURE REVIEW

This section summarises the findings of a review of international and southern African literature on vegetation and groundwater interactions and factors that influence these. The focus of the review has been on finding answers to the three key questions given below:

- ***How deeply do plants root, on average and in particular in phreatophytes, and what are the water use rates and physiological characteristics of phreatophytes?***

- ***What is the impact of a lowering of the water table on obligate phreatophytes? Does the rate at which the water table falls matter?***

- ***Can changes in vegetation cover or vegetation management alter the rate of recharge and depth to groundwater either through its effect on recharge or its direct use of groundwater resources?***

After a brief review of the major processes which affect groundwater recharge and their approximate importance in different situations, each question is addressed in turn and the relevant information summarised below it. The emphasis has been on getting information from South African studies or studies in comparable areas elsewhere in the world and on actual observations or measurements rather than results from models.

3.1 Influence of vegetation on effective rainfall.

3.1.1 *Interception of rainfall by plant canopies*

Interception is the retention of water on the plant surface (leaves, bark) and on litter layers on the soil surface. The amount of water that is retained depends mainly on the area, distribution and orientation of the leaves, their surface characteristics and on the roughness of the bark.

Retained water will either evaporate or reach the soil by stem flow or through flow from the plant or infiltration through the litter. The amount of water that evaporates depends on the relationship between the interception capacity of the vegetation and the rainfall amount and intensity, and the evaporative capacity of the air after the rainfall. In general, interception will be highest for species with dense canopies (a high leaf-area index), rough bark and deep litter layers in areas with low intensity summer rainfall. Conceptually, therefore, interception is best estimated from information about the duration and intensity of each rainfall event. In many cases though this level of detail is not available and methods have been developed based on climatic parameters, vegetation parameters and using daily rainfall instead of rainfall per event. Schulze (1981) has calculated rain-day based interception values for typical South African vegetation types using a model developed by De Villiers (1975 in Schulze 1981) which uses the ratio of mean annual rainfall and mean annual temperature (Table 3.1).

Table 3.1: Examples of ranges in interception per rain-day for different vegetation types in South Africa (after Schulze, 1981).

Vegetation category	Interception (mm/rain-day)
indigenous forest	3.1 - 3.5
bushveld & savanna	1.0 - 4.4
fynbos	0.5 - 2.0
karoo	0.2 - 0.8
grassveld	0.9 - 2.6

In South African savanna, the interception losses for a wide range of rainstorms ranged from 15-20% of the gross rainfall, a significant proportion of the rainfall (De Villiers & De Jager 1981; De Villiers 1982). Scholes and Walker (1993), using models developed by De Villiers (1982), estimated mean annual interception losses in *Burkea* savanna at Nylsvley to be 2 mm per storm. Using a simple water balance model they found this to be equivalent to 35±5 mm per year, 6% of the annual rainfall. Scholes and Walker (1993) estimated that interception losses in grassland similar to that at Nylsvley were about 1 mm per storm. The estimated loss from the grassland litter layer was 1-2 mm per storm. This equates to a mean annual loss of about 24 mm from the grass and 50 mm from the litter, giving a mean total loss of 109 mm or 18.5% of the annual rainfall. They believed this estimate to be about 50% too high but had no data to either support or refute this viewpoint.

International studies show that interception varies significantly between different climate regions and vegetation types (Table 3.2). The highest annual losses are from vegetation areas with light rains (e.g. lower intensity, long duration rainfalls.) The average interception in eucalypt stands is about 16% of rain, which is lower than other forests (pines 24% (n=3), *Acacia mearnsii* 25%, tropical shola forest 34%) largely because of the low leaf area index of the eucalypts (Calder 1992a). The amount of water stored in the canopy of *Pinus radiata* was about twice that of eucalypts because of the high surface area of needle leaves. Studies of a *Banksia* woodland (± 410 trees per ha) and a *Pinus pinaster* plantation (18 years old with 630 trees per ha) found that canopy interception losses were 15-20% of the annual rainfall of 747 mm in both vegetation types, but litter interception may have been higher under pines (Farrington & Bartle 1991). In *Eucalyptus* forest interception was proportional to canopy cover, ranging from 7-20% for 16-25% cover with an annual rainfall of 1100-1220 mm/yr and 1-12% for 2-21% cover at 800-820 mm/yr (Sharma *et al.* 1987b).

Studies in Jonkershoek in the Western Cape (annual rainfall 1300-1700 mm) found that canopy interception losses were 10.3 to 12.2 and 20.0% in 8, 11 and 29 year old *Pinus radiata*, respectively, and 6.3% for *Protea neriifolia* (Versfeld 1988). On the Mpumalanga escarpment interception in pine stands is about 10% and in eucalypt stands about 5% of the annual rainfall (P. Dye pers. comm. 1996).

3.1.2 *Stemflow*

Stemflow is rainwater which, having been intercepted by the vegetation, is directed along the branches and trunk to the soil surface. Stemflow generally averages about 5% of rainfall but can reach as much as 22-40% as found in chaparral and mulga (*Acacia aneura*) woodland (Slatyer 1965; Pressland 1973; Navar & Ryan 1990). In *Protea neriifolia* stemflow averaged 9% of the annual 1500 mm rainfall and in 8-year old *Pinus radiata* 16% of the 1340 mm of rainfall (Versfeld 1988). Table 3.2 shows examples of interception, through fall and stem fall as a percentage of annual rainfall for different vegetation covers in a variety of climates.

Rainfall concentration through stemflow can have a significant impact on soil moisture fluxes in semi-arid environments (Specht 1957; Navar & Ryan 1990; Rhoades 1997). A study of 17 storms, in total 230 mm, over a summer period in Mexico showed that shrubs of *Diospyros texana*, *Acacia farnesia* and *Prosopis laevigata* distributed 4.2% of the net rainfall of 167.6 mm as stemflow. The wetted areas of 0.115-0.320 m² around the stems received the equivalent of 2650-3020 mm of rainfall, 15-18 times the annual rainfall.

No studies of stemflow in herbaceous plants (e.g. tall grasses) were found. Stemflow may be an important factor influencing recharge to groundwater, at least in woody plant communities, but only a limited amount of quantitative data is available at the scale of plant communities or vegetation types (Table 3.2).

Table 3.2: Redistribution of gross rainfall for different woody vegetation types. (After Breman & Kessler 1995).

Vegetation, country + source	Average rainfall or climate	Rainfall event + specifications	Interception losses (%)	Through-fall (%)	Stemflow (%)	Net through-fall (%)
Young spruce, England (Jackson 1975)	Temperate	2.5 mm	64			36
		17.8 mm	21			79
Hardwoods, eastern USA (Helvey & Patric 1965)	Temperate	2.5 mm	40	60	0	60
		20 mm	10	86	4	90
		Annual basis	13			87
Forest trees, Germany (Lunt 1934)	Temperate	Annual basis:				
		- beech	22	65	13	88
		- oak	21	74	6	79
		- maple	23	72	6	78
		- spruce	59	40	1	41
Tropical forest, Surinam (Jackson 1975)	High rainfall	2.5 mm	48			52
		20 mm	21			79

Vegetation, country + source	Average rainfall or climate	Rainfall event + specifications	Interception losses (%)	Through-fall (%)	Stemflow (%)	Net through-fall (%)
Rainforest, Tanzania (Jackson 1975)	High rainfall	2 mm	60			40
		20 mm	12			88
Tropical lowlands forests (Bruijnzeel 1989)	High rainfall	Annual basis	12 - 14	86	0.5 - 2.0	86 - 88
Semi-arid regions *Juniperus occidentalis* California (Young *et al.* 1984)	300 mm	Annual basis				
		- edge of canopy	19			81
		- under canopy	51			49
		- near trunk	69			31
		Total canopy	42	58	0.1	58
Acacia holosericea Australia (Langkamp *et al.* 1982)	1200 mm	10 mm	12	84	4	88
		300 mm	6	67	27	94
		Annual basis	11	73	16	89
Acacia aneura Alice Springs (Slatyer 1965)	275 mm	1 mm	70	30	0	30
		>12 mm	5	55	40	95
Acacia aneura Charleville (Pressland 1973)	500 mm	2 mm	~35	~60	<5	~65
		10 mm	10	68	22	90
		Annual basis	13	69	18	87
Eucalyptus melanophloia Australia (Prebble & Stirk 1980)	700 mm	5 mm	30	70	0	70
		15 mm	~13	87	0.6	~87
		Annual basis	~12	88	0.6	~87
Faidherbia albida Senegal (Dancette & Poulain 1969)	300 mm	<15 mm				95
		>15 mm				120
		Annual basis				110

3.1.3 *Throughfall*

Throughfall is composed of the rainfall that passes through the canopy and that drips from the leaves and branches, some or all of which may be retained by the litter. In species with dense canopies the drips may be channelled to the edge of the canopy, creating a drip zone (Lyford & Quashu 1969).

3.1.4 *Infiltration*

Infiltration is the process by which water moves through the soil surface, into and through the unsaturated soil layers, regolith and under-lying rock under the influence of gravity and hydraulic forces. Some authors use the term percolation to describe the movement of water down through the soil profile and lower layers. Infiltration rates are determined by the surface characteristics and permeability of the soil. This in turn is dependant on soil porosity, wettability of the mineral and organic components of the soil, the soil wetness and viscosity of the water.

Infiltration (and percolation) are far more variable spatially in arid and semi-arid areas than in humid areas where it is controlled largely by pre-event soil moisture (Berndtsson & Larson 1987). In arid and semi-arid areas infiltration is markedly influenced by factors such as the distribution and extent of bedrock outcrops versus soil, differences in compaction in channel and interfluve areas, and vegetation cover. In addition, research has shown that there is marked spatial heterogeneity (horizontal and vertical) in flux rates. This may be the result of wetting front instability (fingering) in where matrix flow is dominant or the result of macropore or preferential flow. Macropores such as desiccation cracks, root canals and fissures act as pathways for relatively rapid vertical infiltration. Most water tends to flow through some form of channel in the soil and regolith rather than infiltration in a uniform front through soil pores.

Clear evidence for preferential flow comes from studies of recharge in deeply weathered profiles (up to 32 m deep) in south-west Australia. Chloride flux analysis found evidence for small scale, localised, very high recharge rates, probably through root channels (Johnston 1983). Heterogenous patterns of chloride flux occurred both horizontally and vertically at a scale of metres (Johnston 1987a). For example, the typical vertical water flux density was 2.2-7.2 mm/year but in a small area it was 50-100 mm/year. The latter rate was much closer to the groundwater recharge rates estimated using the chloride method. At another site with a rainfall of 800 mm/yr the vertical soil water flux density was about 0.4 mm/yr and, at 1150 mm/yr, 2-5 mm/yr (Johnston 1987b). However, chloride based rates of recharge to groundwater were up to two orders of magnitude higher. Preferential flow paths were an important route for recharge with percolation to 6 m taking some 30 years compared with the calculated 1700 years for conduction through the soil matrix (Johnston 1987b). Root channels were apparent in granitic regolith but not below a nodular zone at 3 m depth in doleritic regolith (Johnston *et al.* 1983; Dell *et al.* 1983).

Evidence for preferential flow was also found in dune soils with a rainfall of 300 mm/yr in the Murray River basin in South Australia (Allison *et al.* 1985). In mediterranean Western Australia about 50% of recharge could be accounted for by macropores (including root channels) in a sandy profile and >99% in a highly structured lateritic profile (Sharma *et al.* 1987a). Rapid water table rises were recorded under eucalypt forest but not under grasslands in catchments in southeastern Australia, evidence that continuous macropore pathways were only present under forest (Burch *et al.* 1987).

Isotope studies in Tanzania found that about 60% of the recharge is through macropore and 40% through matrix flow; recharge was 2-3% of the annual rainfall of 550 mm (Nkotagu 1996). Similar heterogenous flow patterns may occur in Karoo soils where even exceptional rains did not wet soil profiles via matrix flow but apparently passed through macropores (Van Tonder & Kirchner 1990).

Studies of infiltration in woody plant communities have found substantial variations between areas under and between trees or shrubs with increasing woody plant cover (Table 3.3). Near stem infiltration rates can be as much as three times the under-canopy and 1.6 times the intercanopy rate (Lyford & Quashu 1969; Rhoades 1997). Tests showed that bulk densities were significantly lower and organic matter was significantly higher under plants. The soil materials under plants were finer, partly due trapping of fine, windblown soil particles. Similar differences of 3-4 times in infiltration rates have been found in coppice (scrub patches) and inter-coppice areas in the Nevada desert (Blackburn 1975).

Changes in vegetation cover can also have marked impacts on infiltration (Table 3.3). Soils are better developed (finer texture, more organic matter and nutrients) under oak patches in mediterranean shrubland, resulting in enhanced infiltration and storage capacity (Valentini *et al.* 1991; Dawson 1993c). Clearing of eucalypt forest reduced infiltration rates; saturated hydraulic conductivity decreased 10-fold and sorbtivity 3-fold (Sharma *et al.* 1987b). A grassland catchment (eucalypt forest cleared 80 years previously) generated high-peak stormflows and large discharge volumes regardless of antecedent moisture levels. This differed strikingly from a similar forested catchment which produced little runoff until antecedent soil water was high (>60% capacity) (Burch *et al.* 1987). The primary cause was that subsurface (0.1-0.4 m) hydraulic conductivities under grassland were about half those of undisturbed forest catchments. In the arid mid-west of the USA infiltration rates are high with no overland flow on undisturbed sites but where vegetation is degraded or absent 40-60% of the rainfall becomes surface flow (Croft 1950). Similar variations have been recorded in a study in savanna in West Africa (Table 3.4), and in sem-arid karoo veld in South Africa (Milton and Dean 1996).

Table 3.3: Relative water infiltration rates in relation to soil texture and presence of a woody canopy, from studies in semi-arid regions. After Breman & Kessler (1995).

Country + source	Soil texture	Canopy specifications	Relative infiltration rate (%)
Zimbabwe (Kennard & Walker 1973)	Sandy	Closed canopy	100
		Open canopy	84
		Open grassland	55
Zimbabwe (Kelly & Walker 1976)	Variable	Complete litter cover	100
		Partial litter cover	33
		No litter cover	12
Kenya (Belsky *et al.* 1989)	Loamy	Under canopy *A. tortilis*	100
		Open field	25
		Under canopy *Adansonia*	100
		Open field	20
Kenya (Scholte 1989)	Loamy	Under shrub	100
		Open field	5
Australia (Slatyer 1961)	Sandy	0.5 m from tree stem	100
		2.0 m from tree stem	60
		Open field	40
New Mexico (Elkins *et al.* 1986)	Variable	*carrea tridentata* canopy	100
		Medium cover grassland	92
		Low cover grassland	87
Arizona (250 mm/yr) (Lyford & Quashu 1969)	Loamy	Near stem	4.01-6.44 (mm/min)
		Under canopy	2.12-4.80
		Inter-canopy	0.94-2.60
Nevada (Blackburn 1975)	Loamy	Coppice - dry	64.5-73.4 (mm/hr)
		Field capacity	58.2-72.1
		Coppice - dry	26.2-50.5
		Field capacity	16.5-32.0

Table 3.4: Run-off and drainage beyond 1.80 m soil depth at three sites with sandy-loam soils, in West Africa (Roose 1981; in Breman & Kessler 1995)

	Adiopodomé	Korhogo	Gonsé
Average annual rainfall (mm)	~ 1700	~ 1200	~ 700
Average run-off (% of rainfall)			
- natural vegetation	0.5	2	7.6 (1.5-24)
- cropland	22	20	16.5
Average drainage at 1.80 m depth (mm)			
- natural vegetation	78.5	23	15.4 (0 - 49)
- cropland	39	25	1.5

Grazing alters soil compaction, reducing infiltration. In a 3-year study, grazing did not alter seasonal soil water recharge and depletion patterns (Naeth *et al.* 1991). Grazing reduced soil water most in the wet season with the least difference occurring toward the end of the dry season i.e. in ungrazed grass the higher water-use was less than the increase in infiltration and decrease in soil evaporation. The higher infiltration rates in ungrazed grassland were due to lower bulk density, lower penetration resistance (soil strength) and greater litter mass (organic matter input). High intensity or early grazing had a greater impact than other grazing regimes. Water infiltration rates were significantly higher under tree canopies than in grassland in lightly grazed areas but not in moderately to heavily grazed areas where it was slightly lower under trees (Belsky *et al.* 1993).

Land degradation typically increases exposure of the soil surface. Infiltration rates are positively related to litter and basal cover, being up to 9 times faster with 100% litter cover (O'Connor 1985). On red soils in the Matopos infiltration in degraded veld was <50 mm/hr compared with 100-200 mm/hr on good condition veld (Barnes and Franklin 1970, cited by O'Connor 1985). Data from a bare and a grassed lysimeter showed that about half of the runoff from the bare soil lysimeter occurred as overland flow, the rest being deep drainage (Hino *et al.* 1987). Overland flow scarcely occurred from the grassed lysimeter. Grass roots that penetrated deep into the soil layer played an important role in increasing the infiltration rate as well as in drying the soil uniformly. Reductions in infiltration caused by compaction and exposure of soil surface by poor land-use practices may have depleted soil moisture reserves and resulted in the death of baobabs in the Messina area (Caplan 1995).

Above we have shown how plant characteristics and relative abundance of plants can affect the partitioning of rainfall. The other major impact of plants on groundwater recharge and discharge are a consequence of water extraction by roots from the unsaturated and saturated zones of the soil, or regoliths where they occur. There are numerous reports of changes in evapotranspiration following changes in land-cover but a summary of this work falls outside the aims of this review. Briefly, evaporation from plant canopies increased in relation to the stature, complexity and aerodynamic roughness of the canopy, and in relation to rooting depth of seasonal characteristics of the vegetation type. Information on aspects which relate to groundwater recharge and the important factors in recharge is addressed under the key questions below.

3.2 Key Questions

The key questions posed below identify research areas which are fundamental to understanding vegetation- groundwater interactions in South Africa.

3.2.1 *How deeply do plants root, on average and in specialised phreatophytes, and what are the water use rates and physiological characteristics of phreatophytes?*

3.2.2.1 Direct observations of the depths of roots systems

In general, studies of root systems in plants show that roots will penetrate as deeply into the soil as is required to reach available water, being restricted only by soil or regolith characteristics that prevent rooting or by permanent water tables (Cannon 1949; Stone & Kalisz 1991; Nepstad *et al.* 1994; Stone & Comerford 1994; Canadell *et al.* 1996; Jackson *et al.* 1996; Table 3.5). Although deep roots may only comprise a small fraction of the system they may be critical for plant survival. Just a few roots penetrating apparently impenetrable soil layers (e.g. massive laterite layers) can sustain even large trees (Doley 1967; see Stone & Kalisz 1991). Many shrub species have roots penetrating 3-10 m or more where this is possible (Hellmers *et al.* 1955; Specht & Rayson 1957; Dodd *et al.* 1984).

Deep rooting is not only found in woody plants: herbaceous plants such as lucern (*Medicago*) may reach depths of 10s of metres (Stone & Kalisz 1991; Stone & Comerford 1994; Jackson *et al.* 1996). Many, but by no means all, savanna trees are commonly deep rooted, with legumes such as *Acacia* and *Prosopis* reaching depths of 3-20 m and even >53 m in one recorded case. *Eucalyptus* is another genus which has deep root systems, commonly reaching 10 m and reported to 60 m in one case. Many species in arid and semi-arid environments have shallow, spreading root systems which are used primarily to scavenge water for storage in the plant; these include most succulents such as cacti, aloes and even the baobab *Adansonia digitata* (Caplan 1995; Table 3.5). A number of evergreen tropical forest species also have deep root systems (> 8 m), enabling them to survive periodic droughts (Nepstad *et al.* 1994). Root systems can develop rapidly: *Pinus radiata* roots reached a depth of 2.6 m four years after germination; *Robinia pseudacacia* 3.7 m four years after planting.

Plants in desert environments can be grouped according to their root systems and tolerance of moisture stress (Nobel 1991):

- xerophytic ferns/ lichens, mosses - root system mean depth 0.07 m, max 0.13 m; these species are often confined to rocky areas with shelter from full sun and moisture in cracks; found mainly in coastal deserts;

- annuals - depth 0.01, max 0.3 m;
- perennial grasses - depth 0.33-0.36, max 1.0 m; wetter deserts, especially with summer rainfall;
- drought deciduous shrubs - depth 0.2-0.8, max 0.2-1.9 m; most common in deserts with predictable, seasonal rains; generally shed leaves at -4 to -5 MPa moisture stress, occasionally -10 MPa;
- evergreen shrubs - depth 0.2-0.7, max 0.5-2.2 m; widespread and dominant in many deserts; able to remain active at very high moisture stress levels;
- phreatophytes - depth 5, max 4-12+ m; species able to grow roots to depths needed to tap water tables or other relatively stable water sources;
- desert succulents - depth 0.07-0.12, max 0.15-0.77 m; widespread in a variety of deserts; capable of rapid root growth following rain, often with roots as shallow as 0.03 m.

There will always be exceptions to categories. For example, *Trianthema hereroensis* which is a Namib desert dune plant with succulent leaves (Nott & Savage 1985). It has a dimorphic root systems varying from spreading (<6 m) to descending like taproots where water is available at deeper levels (e.g. 2 m).

Tap roots in *Acacia* species may reach 35 m depth and many species also have wide spreading lateral roots (50 m); many other tree species are also potentially deep rooted (e.g. *Commiphora, Boscia)* (see also Leistner 1967; Cole 1986; Canadell *et al.* 1996). *Atriplex* species vary from obligate phreatophytes which need direct access to water (whether ground or surface) to facultative phreatophytes (able to use but not entirely dependant on groundwater) (Le Houerou 1992). In some species e.g. *Atriplex nummularia* (which is common in South Africa) roots may reach water tables at >10 m depths. Phreatophytes are no exception to the deep rooting habit, although the depths are often limited by permanent water tables rather than physical ability (Zoth & Block 1992). Examples include: *Acer* species 4 m; *Prosopis* species 3-15 m, maximum >53 m; *Melia* species 3.9 m; *Eucalyptus camaldulensis* 9 m; *Fraxinus* species 6.1 m; *Populus* species 3.6 m; *Salix* species 4.2 m (also known for spreading root systems).

The generally held assumption that roots are shallow, and that the important parts for ecosystem function are those at < 0.5 m, has recently been re-evaluated. New conclusions are that deep root systems are pervasive and play key roles in ecosystem functioning and in water and nutrient fluxes (Canadell *et al.* 1996; Jackson *et al.* 1996) .

3.2.1.2 Isotopic evidence for the depths of root systems

Studies of the relationships between the stable isotope composition of water in plant sap and water at different depths in the soil can provide valuable information on plant root systems and their distribution (Rickard & Price 1989; Stringer *et al.* 1989; Flanagan *et al.* 1992a, b; Dawson 1993a; Thorburn *et al.* 1993; Brunel *et al.* 1995; Thorburn & Ehleringer 1995; Schulze *et al.* 1996).

Table 3.5: Characteristics of root systems of woody species occurring in Africa, including indication of the root system type. [1 = deep roots and few superficial roots; 2 = deep roots and many superficial branch roots; 3 = shallow and extending roots.] After Breman & Kessler (1995).

Country, rainfall, literature source	Woody species	Root System						Type
West Africa, Senegal 300 mm (Bille 1977)		Depth (cm) (% roots at each depth)						
		0-20	20-50	50-100	100-200	200-400	>400	2/3
	Adansonia digitata	33%	33%	20%	13%	1%	-	2
	Balanites aegyptiaca	35%	23%	19%	15%	7%	1%	2
	Acacia senegal	33%	24%	19%	15%	6%	2%	3
	Commiphora africana	65%	21%	8%	5%	2%	-	2
	Guiera senegalensis	41%	27%	16%	11%	4%	1%	3
	Grewia bicolor	72%	10%	15%	3%	-	-	
Mali, 500 mm (Penning de Vries Unpubl.)	*Acacia seyal*	Predominantly shallow, deep taproot (>5 m) lateral extension 5 x crown radius (5 - 10 m)						2
	Bombax costatum	Predominantly shallow, short taproot (<1 m) lateral extension 7 x crown radius (10 - 35 m)						3
	Boscia senegalensis	Predominantly at 0.5 - 1.5 m depth						3
	Combretum ghanalensis	Like *Acacia seyal*						2
	Guiera senegalensis	Predominantly shallow, no taproot lateral extension 5 x crown radius (4 - 6 m)						3
	Pterocarpus lucens	Very shallow roots (<0.5 m)						3
Sahel region (Wickens 1980)	*Acacia senegal*	Deep tap root reaching water table, extensive lateral roots						2
Sahel region (von Maydell 1986)	*Prosopis juliflora*	Deep tap root (up to 35 m)						½
Sahel region (CTFT 1988)	*Faidherbia albida*	Sandy soils: deep tap root reaching water table (40 m?)						1
		Valleys: predominantly shallow roots						2
Sahel region (pers. obs.)	*Vitellaria paradoxa*	Predominantly shallow, large taproot not very deep (about 2 m)						2
	Parkia biglobosa	Predominantly shallow, short taproot (< 2 m)						2
Other semi-arid African regions								
Sudan 500 mm (Adams 1967)	*Acacia mellifera*	Shallow roots only (0 - 60 cm), extending laterally 8 - 15 m						3
	Acacia seyal	Predominantly shallow, extending laterally 8 m, taproot until 1.2 m depth						2
	Balanites aegyptiaca	Predominantly shallow, extending laterally 7 m, taproot until 1.3 m depth						2
Sudan 700 mm (van Noordwijk 1984)	*Acacia seyal*	Taproot reaching 1 - 2 m depth, shallow						2
	Acacia senegal	Roots at 20 - 60 cm depth, laterally						2
	Balanites aegyptiaca	Extending to 8 m from trunk						2
Kenya 450 mm (Belsky et al. 1989)	*Acacia tortilis*	Shallow roots with a deep taproot reaching groundwater						2
	Adansonia digitata	Very shallow root system						3
South Africa 630 mm (Knoop & Walker 1985)	*Burkea africana*	Root biomass concentrated at depth 50 - 60 cm						2
	Ochna pulchra	Root biomass concentrated at depth 20 - 40 cm						2/3
	Terminalia sericea	Root biomass concentrated at depth 12 - 23 cm						2/3
Kenya 300 mm (Fenner 1980)	*Adansonia digitata*	Maximal depth 1.8 m maximal lateral extension 44 m						3

Studies in North America show that herbaceous plants extract most water from 0.15-0.80 m below the surface while for woody plants the typical depths are 0.30-1.50 m or more (Dawson 1993a). Some trees (e.g. Swamp cypress) use groundwater rather than surface water even in swamps. Others (e.g. *Pinus strobus*) use rainwater on dry sites and groundwater on wet sites, also showing a shift from rain to groundwater as the profile dries out. Broad-leaved, deciduous riparian species (*Acer, Populus, Betula, Fraxinus, Salix*) use groundwater rather than surface water, except when small. Plant water-use also depends on the development of their root systems. One study showed that mature trees along a perennial stream used little or none of the surface stream water and extracted water from deeper layers although roots were distributed through the profile (Dawson & Ehleringer 1991). Small streamside individuals used stream water while small non-streamside individuals used mainly recent precipitation. Recruitment may thus depend on sustained surface water supplies but larger trees preferentially use subsurface water to decrease risk of mortality during drought. A similar relationship between age (size) and water extraction depth has been reported in other species (Donovan & Ehleringer 1994).

Water-use patterns of *Eucalyptus camaldulensis* varied with differing exposure to streamwater in a riparian situation where streamwater and groundwater are disconnect. (Thorburn & Walker 1994; Thorburn & Ehleringer 1995). Trees with permanent access to streamwater used about 50% from soils or the water table and 50% streamwater. Those beside an ephemeral stream with access to streamwater for 40-50% of the time used 30% streamwater. Trees with ephemeral access to streamwater (only during floods) used only groundwater even during two months of inundation. Trees with continuous access to streamwater experienced lower water stress and had lower water-use efficiency (WUE) than trees at the driest site. Trees near the ephemeral stream reduced their WUE when streamwater was available. Uptake of soil and groundwater is advantageous because it has higher nutrient levels and is a more reliable source.

Water-use efficiency during photosynthetic gas exchange, calculated from leaf carbon isotope composition, differs among species, with shallow rooted species having the highest WUE and deep rooted species the lowest (Flanagan *et al.* 1992b). Phreatophytic species (*Populus, Salix*) mainly used groundwater or saturated soil water sources (Busch *et al.* 1992). The exotic *Tamarix ramossissima* appeared to use both the deeper water resources and water from unsaturated alluvial soils (see also Sala *et al.* 1996). *Prosopis velutina* is a facultative phreatophyte, able to survive outside riparian areas but growing best in riparian habitats (Stromberg *et al.* 1993). It is typically a shrub where groundwater tables are deeper than about 15 m, and canopy height varies with depth to groundwater. The degree of water stress increased with increasing depth to the groundwater table. This species is also able to adapt physiologically to reduce stress by osmotic adjustment and by seasonally varying its stomatal sensitivity to vapour pressure deficits. This behaviour is similar to that of other winter-deciduous desert phreatophytes (*Acacia greggii, Olneya tesota*) which showed more flexibility than evergreen phreatophytes (*Larrea tridentata, Simmondsia chinensis*) (Nilsen *et al.* 1994). Summer deciduous phreatophytes (*Hyptis emori, Chilopsis linearis*) minimised stress by maintaining low leaf biomass and low summer leaf conductances, while a stem photosynthetic species (*Dalea spinosa*) had almost no leaves.

Several shrub and tree species in the Mediterranean region of Western Australia show seasonal shifts in water extraction patterns (Dawson & Pate 1996). When the surface layers are moist they get most water from well developed lateral roots. As the soil profile dries out, they extract water from deeper layers using sinker roots; water from these roots also maintains hydration of the lateral roots. Hydraulic conductivity of sinker roots is substantially higher that of lateral roots, mainly due to the very long xylem vessels (1.5 - 2.0 m) in the former (Pate *et al.* 1995). Differences in root anatomy between the tap roots and other roots have been recorded in a Cape *Protea* species (Higgins *et al.* 1987).

3.2.1.3 Characteristics of different root systems

Studies of diurnal and seasonal water relations show that species able to maintain root systems in contact with groundwater tables have high transpiration rates and show little seasonal variation in water stress compared with more shallow rooted species (Crombie *et al.* 1988; Crombie 1992; Dodd & Bell 1993). Some species' rooting habits are also related to their tolerance of moisture stress (Davis 1995; Davis & Mooney 1986; Pockman *et al.* 1995). Shallow-rooted species were highly resistant to the formation of xylem embolisms under stress whereas deep-rooted species were relatively susceptible. Transpiration rates in *Acacia ehrenbergia* varied according to the accessibility of groundwater (Ullmann 1985). Trees rooted in the groundwater table transpired more than those in a gravelly runoff line and, in turn, more than trees in a sandy depression. The latter showed a midday depression in transpiration, indicative of moisture stress.

The habit of pre-rains flowering and leaf flushing in many savanna tree species appears to be associated with deep root systems which can access moisture in the deep soil layers and regolith (Cole 1986). Measurements of summer water potentials and responses to vapour pressure deficits suggest that *Elytropappus, Lebeckia cytisoides* and *Galenia africana* (south-facing slopes only) are deep-rooted like other desert species with similar behaviour (Midgley and Bösenberg 1990). *Pteronia incana, P. paniculata, Osteospermum sinuatum* and *Galenia africana* (north slopes) behaved as shallow-rooted species with high moisture stress levels (>4 MPa) for several months in summer. *Rhus incisa* and *Dodonea viscosa* exhibited intermediate behaviour.

In North American desert communities, annuals and succulents depend very largely on summer rainfall (Ehleringer *et al.* 1991; Rundel *et al.* 1991). Groundwater or winter rainwater use is somewhat higher in herbaceous perennials followed by woody perennials (*Artemisia, Pinus edulis*) with spreading root systems, while deep rooted perennials (*Juniperus osteosperma, Chrysothamnus nauseosus*) almost exclusively use winter rains and groundwater. These trends correlated well with water-use efficiencies, with the deep rooted plants having the lowest water-use efficiency (Flanagan *et al.* 1992a).

There is also evidence of genetic variation within species in their root system development and plasticity and root physiology. Examples are *Nyssa sylvatica* in North America (Keeley 1979) and *Eucalyptus camaldulensis* (Awe *et al.* 1976).

3.2.1.4 Studies of root systems in Southern Africa

Studies of root systems at a typical savanna at Nylsvley (rainfall 630 mm per year) showed that most species had extensive lateral root systems (Rutherford 1983). In *Ochna pulchra* roots extended up to 4 m from the stem and "individuals" were often connected to others by lateral roots to form clones. Most roots were in the upper 0.6 m; roots penetrated the gravel layer but stopped at the bedrock (2.2 m depth). *Burkea africana* root systems spread up to 20.5 m from the tree, most roots were in the upper 0.4 m; "heart" roots (near stem base) and occasional sinkers reached bedrock. In *Terminalia* the root system was primarily shallow and spreading at 0.12-0.35 m depth and 3.6-6.6 m from the stem. Tap-roots penetrating beyond 1.52 m were observed by Strang (1969), but most roots of grasses in this savanna were in the 0-200 mm layer and trees in the 150-610 mm soil layers.

General descriptions of the root systems of many widespread shrub species and some grasses of the semi-arid and arid regions of South Africa, with emphasis on the winter rainfall region, are given by Van Breda & Barnard (1991). *Acacia karoo* is one of the most widespread and versatile of southern African acacias (Barnes *et al.* 1996). In the most arid parts it will only grow where it has access to permanent underground water as it is not very drought tolerant. Seedling mortality occurs when conditions prevent adequate growth before soils dry out (Barnes *et al.* 1996). Roots of *Elytropappus rhinocerotis* (renosterbos) in soil with 240-300 mm of loam over weathered shale in the Worcester area penetrated to 6.1 m in dry soils but were shallower (1.2-3.0 m) in moister profiles (Scott & Van Breda 1937a). Roots of *Galenia africana* are known to reach 7 m depth in deep soils but development is sensitive to soil and water conditions (Scott & Van Breda 1937b).

Root development of black wattle (*Acacia mearnsii*) is rapid and precocious, reaching several centimetres depth before the plumule emerges (Sherry 1971). Lateral root growth is rapid and lateral roots extend out to a greater radius than the height of the tree when not restricted by limited growing space. Sinker roots descend from the laterals and may reach depths of 15 m or more if the profile permits this, but the tap root is generally shallow (<1.5 m).

3.2.1.5 Summary

How deeply do plants root, on average...

The depths of plants root systems are highly variable and in many cases roots extend much deeper than the shallow, agriculturally - defined soil profile. The main constraints on root depth appear to be the penetrability of the soil or regolith, the depth to the permanent water table and the inherent rooting behaviour of the plant. Most plants have the bulk (>70%) of their roots situated in the upper 0.5-1.0 m of the soil profile. This does not necessarily mean that they extract the bulk of their water from this zone. Sinker roots occur fairly often but are apparently difficult to detect except when studies involve complete excavations or deep trenches. Herbaceous annuals, desert ephemerals and succulents typically have shallow roots (<0.3 m), herbaceous perennials usually have relatively shallow root systems (<1.5 m). The depths of the root systems of woody plants are highly variable with mean maximum depths of 7.0 ± 1.2 m for trees and 5.1 ± 0.8 m for shrubs (Canadell *et al.* 1996). Deep rooting is recorded for herbaceous plants (10's of metres) and woody plants (to > 50 m for Acacia and Eucalyptus).

...and in specialised phreatophytes?

There is no evidence that phreatophytes have a single root system type or rooting depth. There are species which are confined to riparian systems, but these are apparently not limited to situations with shallow groundwater. Two groups of phreatophytes can be distinguished: obligate phreatophytes and facultative phreatophytes. The latter species have the ability to develop deep root systems (generally > 1.5 m), enabling them to tap deep soil or groundwater resources to maintain high transpiration rates.

Generally obligate phreatophytes appear to have the lowest tolerance for moisture stress although other factors may determine their distributions. For example, it seems that poplar species need wet soils and high water tables for successful seedling establishment with adults being more tolerant moisture stress (but see also the next section). Facultative phreatophytes may be more moisture stress tolerant but seedling establishment appears to be confined to high rainfall periods, suggesting that high water contents are needed to minimise mortality. All phreatophytes appear to share the following traits:

- ➢ relatively low moisture stress tolerance compared with other plants due, at least in some species, to the structure of their wood and conducting vessels which make them prone to the formation of embolisms;
- ➢ high transpiration rates all year round with little if any decline at midday in summer and low water-use efficiencies; in some cases transpiration may be close to potential evaporation or even exceeds it; (for more information see section 3.2.3); and
- ➢ some species appear to rely primarily or entirely on groundwater rather than the water from unsaturated zone regardless of how much water is available in the unsaturated zone (see also the next section).

3.2.2 *What is the impact of a lowering of the water table on obligate phreatophytes? Does the rate at which the water table falls matter?*

There have been a few studies of the effects of lowering of the water table on plants and vegetation communities. All those found in the course of this literature survey deal with riparian and wetland vegetation (i.e. discharge areas). None dealt with vegetation in other situations in the landscape.

3.2.2.1 Riparian systems

Riparian specialists or obligate phreatophytes are plants adapted to fluctuating water tables and their roots remain in contact with the saturated zone. These species are sensitive to sudden water stress e.g. a sudden lowering of the water table (Rood and Mahoney 1990; Mahoney and Rood 1991, 1992) or changes in flood durations (Smith *et al.* 1991). Seedling studies of poplars have shown that rooting depth tracks water table depth. Seedling survival was >90% with a water table reduction of 1 or 2 mm/day, but was only 40% and <25% with reductions of 4 and 8 mm/day, respectively. Decreases in growth of seedlings with a drop in water table levels were greatest in coarse, gravelly profiles and least in sandy profiles because of the faster drainage in the unsaturated zone of the former.

Similar findings have been reported in comparisons of sands, loams and peaty substrates (Schwinzer and Lancelle 1983). Plants grown experimentally showed slower growth and greater allocation of resources to roots where water tables were deeper (Schwinzer and Lancelle 1983; Mahoney and Rood 1992). The growth form of *Prosopis velutina* ranges from a shrub where the groundwater table is deeper than about 15 m to tall trees (12 m) where water table depths are < 6 m (Stromberg *et al.* 1993). Permanent lowering will cause a continual and quantifiable decline in height and structural complexity, mortality, and eventual replacement by desert scrub.

Riparian zones, especially in semi-arid to arid areas, are important areas for biodiversity, offering refuges and habitat for a variety of organisms (Naiman *et al.* 1993; Morrison *et al.* 1994). The convergence of surface and groundwaters in floodplains, alluvial aquifers and hyporhoeic zones is an important factor determining landscape morphologies and their biodiversity and productivity (Stanford & Ward 1993). This is partly a consequence of groundwater carrying higher quantities of nutrients than surface waters, with the latter usually being better oxygenated. Groundwater discharge creates patches of high productivity in the hyporhoeic zones and aquatic systems which support greater animal densities and diversity compared with non-discharge situations. In many situations riparian plants are tapping interstitial rather than surficial flows. Groundwater abstraction may severely affect these systems.

Stream diversion through dam construction alters water tables and flood durations, increasing the levels of water stress in riparian vegetation below the point of abstraction (resulting in reduced canopy leaf area and xerophytic leaves) and reducing biodiversity (Keeley 1979; Smith *et al.* 1991; Stromberg 1993; Stromberg *et al.* 1993). Abundance (in terms of foliage area, stem basal area, stand width) of mixed deciduous riparian forest in a semi-arid basin in Arizona increased significantly with increasing growing season flow volume, a surrogate measure of riparian water availability (Stromberg 1993). Species richness increased with flood size, possibly peaking at intermediate values. Phreatophytic species are particularly vulnerable because they are unable to withstand more than moderate water stress. The risk of mortality among juvenile plants is increased and may eventuate in recruitment failures, at least in poplar species (Rood & Mahoney 1990). Sudden changes in water tables (e.g. through damming of rivers) may cause severe stress, partial or complete mortality in large trees (30+ years old for poplars) which can not grow their root systems rapidly enough to maintain adequate water supplies to their extensive canopies. The losses (e.g. reduction in abundance and species) may show lags of years to decades before becoming evident because it may require exceptional droughts to pass stress thresholds and initiate mortality. Species growth rates may also decline when flooding is reduced (Johnson *et al.* 1976). Changes in flooding also alter scouring patterns, especially on meandering river systems and can reduce or prevent regeneration of species which require exposed alluvial soils for establishment (e.g. poplars).

There has been considerable concern about the health of the extensive riparian eucalypt forests in the Murray River basin in Australia. The dominant eucalypts use a significant proportion of groundwater. *Eucalyptus camaldulensis* trees with permanent access to streamwater extracted about 50% of their water from the water table; those beside an ephemeral stream 70% and those exposed to surface water only during floods used only groundwater (Thorburn & Walker 1994).

Similar patterns were recorded in another study: *Eucalyptus camaldulensis* and *Eucalyptus largiflorens* on the Murray River floodplains used only groundwater in more than half the samples and groundwater comprised 40-80% of the remaining samples (Thorburn *et al.* 1993). In *E. largiflorens* extraction depths ranged from 0.2-4.0 m, and for *E. camaldulensis* from 0.1-3.2 m. River regulation has decreased winter and spring flows and prolonged summer and autumn flooding and this has adversely affected the forest dynamics (Dexter *et al.* 1986). Leaf areas, xylem pressure potentials and relative growth rates were higher in *Eucalyptus camaldulensis* trees with shallow groundwater or close to flood channels (Bacon *et al.* 1993). Significant increases in moisture stress were detected for 22.5-37.5 m away from channels. Short-term flooding of channels comprising 15-20% of the area, enhanced growth over about 70% of the forest. The relative dominance of rush, grass and forest vegetation is also determined by flooding regimes: rushes require more-or-less permanent wetland conditions, forest the driest conditions; grasslands are able to resist tree invasion as long as flood frequencies and durations are intermediate (Chesterfield 1986). Die-back of *Eucalyptus largiflorens* in the Chowilla region is directly related to the depth and salinity of saline groundwater which, in turn, is related to changes in land-use in the adjacent areas (Jolly *et al.* 1993).

The dynamics, structure and biodiversity of riparian forest on the Tana River in Kenya is directly related to the maximum frequency, timing and duration of flooding (Hughes 1990). Tolerance to flooding is particularly important as prolonged inundation drowns most species. Regeneration depends strongly on the seedlings' ability to reach groundwater before the soil water dries out. Evergreen forest types experienced flooding at intervals of 1.9-3.8 years.

Similar patterns were inferred for the Pongola River flood plain communities (Furness & Breen 1980; Heeg & Breen 1982). *Acacia xanthophloea* communities tended to occur on higher ground than *Ficus sycomorus* communities. Both vegetation types are dependent on easy access to water while being sensitive to flooding, requiring well drained upper soil layers (*Ficus* more so than the *Acacia*).

Riparian wetlands in South Africa are an important habitat but there is very little information on them and their dynamics (Rogers 1995). Although they comprise only 19.1% of the area, washes (16.6%) and major river courses (2.5%) in the Karoo provide a habitat for a number of plant and animal species (Milton 1990). River courses had the highest plant species richness and structural diversity and were distinct from the plains and heuweltjies (hummock) communities. The riparian vegetation included *Acacia karoo, Euclea, Rhus, Carissa, Lycium* and other genera that are more typical of savanna but are able to persist by tapping water in the alluvial and karoo sedimentary rocks. These trees, together with their understorey, provide a habitat for many animal and insect species.

During the period from 1979/80 to 1982/83 the Kuiseb River in Namibia did not flood, and the water table in a section of the river bed dropped by 3 m (Ward & Breen 1983). A number of large *Faidherbia albida* trees (riparian fringe woodland) died and the growth and vitality of riverine vegetation declined. Localised stands of young *A. albida* (established 1974 and 1976) have survived suggesting that the large (older) dead trees had lost their ability to adjust to rapidly receding water table. *Acacia erioloba*, which occurs elsewhere outside of a non-riparian zones, had shown not shown any signs of mortality, perhaps because it is less dependent on readily available groundwater. In another study on the lower Kuiseb River, total annual evapotranspiration from the well developed river fringe woodland of *Faidherbia albida, A. erioloba, Euclea pseudebenus* and *Tamarix usneoides* was estimated at about 24% of the total aquifer volume, equivalent to a drying-out depth of about 2.92 m, 2.27 from transpiration and 0.67 m from evaporation from the sand (Bate & Walker 1993). Transpiration was equivalent to about 658 mm/year and evaporation from the sand about 186 mm/year. *Faidherbia albida* seedlings have root growth rates of 100 mm/week and are able to keep pace with the falling water table. *Acacia erioloba* as a seedling is much slower growing and may only establish in wet years, suggesting it is more vulnerable to rapid drying of the riparian profile due to groundwater extraction by pumping. The normal volume in the unexploited aquifer is such that there is a buffer between floods; good floods may even supply sufficient water to last five years. Abstraction, especially in a season without floods, could lead to aquifer depletion and an increase in tree mortality. The woodlands may then establish a new "equilibrium" density or possibly even collapse completely.

3.2.2.2 Wetlands

Wetlands provide key (e.g. breeding, nesting) habitat for many animals, including frogs and other amphibians which are primarily terrestrial but require water for reproduction (Hollis & Bedding 1994; Cowan 1995a; Pressey 1986). Thus the indirect impacts of wetland degradation can be substantial. The primary causes of wetland destruction around the world are surface drainage, to transform them into arable land, and contamination with chemicals (Llamas 1991). There are surprisingly few cases reported where the loss of wetlands or wetland function has been attributed to exploitation of groundwater in arid or semi-arid countries or regions. An example is the lack of documented cases from the arid western USA although there were probably many wetlands, perhaps because they were destroyed before concerns were raised.

Factors which influence the impacts of groundwater abstraction on wetlands are (a) whether it is a recharge or discharge landscape segment, and (b) the type of connection with the regional aquifer (Bernaldez *et al.* 1993). For wetlands connected to a regional scale aquifer, factors affecting the groundwater geochemistry are important. These include the nature of the host rock and the flow length and residence time of the groundwater. A comparison of the hydrologic regimes of two apparently similar wetlands showed that they differed in their behaviour because one had a continuous and one an ephemeral connection to a local upland groundwater system (Devito *et al.* 1996). This means that analyses of the role of groundwater in wetlands need to take into account the degree of hydraulic continuity in the system and its variation during the annual cycle.

Most wetlands are groundwater discharge areas, the exception being small closed basins perched over local phreatic surfaces, which are thus recharge rather than discharge zones. Drawdown of the water table generally transforms wetlands from discharge to recharge zones, altering both the soil water regime and water chemistry, both of which affect the vegetation and fauna. In Spain, ecological degradation of wetlands occurred before the traditional indications (e.g. lowering of groundwater table) became evident (Suso & Llamas 1993). The Tablas swamps are fed by groundwater and two rivers: one surface runoff fed, one groundwater fed. The swamps were perennial except in the driest summers. Abstraction from the aquifer for irrigation transformed much of the swamps into a recharge area, the wetlands shrinking from 15-20 km² to 0.7 km² with a loss of the typical communities. Since the Tablas wetlands have dried out they have become fire prone with more than 8 km² being burnt, including areas with deep organic material (Llamas 1988). The Doñana wetlands face the same fate. In Doñana the worst affected area will be the ecotone (transition zone) between the marsh and the moving or stable dune sands. Water table declines between 1970 and 1987 ranged from 0.91-1.2 m per year, resulting in wetland losses in different areas of 39.0-74.4% (Bernaldez *et al.* 1993). These losses also affect wildlife as evaporative cooling had created milder local microclimates. The microclimate, together with the diverse wetland flora, sustained a diverse insect fauna, which in turn fed insectivorous ground birds (e.g. bustards), water birds and vertebrates.

In Spain, especially in semi-arid regions, there are areas where the effluent flow only rarely reaches the surface, being apparent only in the transpiration of plants, typically phreatophytes, which may have 10 m deep root systems (Bernaldez *et al.* 1985). These areas of evaporative discharge (about 600 mm/yr) provide energy (heat) sinks of micro or local climatic importance and have a high amenity value (e.g. air temperature 7°C cooler and relative humidity 14% higher). They form islands of high biodiversity and provide key habitats. Even small changes in water levels are important because they lower water tables beyond the reach of roots. These areas also lack the buffering of surface water flows to protect them from the impacts of groundwater abstraction or changes in local hydrology due to trenching and deep road or railway cuttings.

Many wetlands in South Africa also have been abused and some are in a seriously degraded state (Cowan 1995a).

3.2.2.3 Summary

What is the impact of a lowering of the water table on obligate phreatophytes?

Exploitation of groundwater resources can have a significant impact on both riparian and wetland communities, especially wetlands that dependent on access to groundwater. Raising the water table can be as harmful as lowering and so can alterations of the seasonal and interannual variations in flood frequencies and depths. These impacts can be subtle; for example lowered water tables can prevent seedling recruitment and alter vegetation dynamics with little obvious impact in the short term. Community responses can also be delayed until, for example, droughts or high abstraction rates, or both, lower the water table to the point where it passes the threshold of community resilience and there is mass mortality.

The available evidence suggests that the extent of the impact does seem to be related to the rate at which the depth of the water table changes, but it is risky to generalise from the little that is known.

3.2.3 *Can changes in vegetation cover or vegetation management alter the depth and recharge of groundwater?*

Changes in vegetation cover or management with associated changes in the rates of transpiration, interception, infiltration runoff and the depth of rooting can alter groundwater recharge. Changes in the rate of recharge will affect the depth of the water table and may also influence groundwater quality. Changes in interception and infiltration were discussed above, this section concentrates on the impacts of vegetation change on groundwater recharge.

Indirect evidence for altered recharge comes from catchment-based studies on the effects of afforestation and deforestation on streamflow. These showed that a 10% change in cover in evergreen (e.g. eucalypt, pine) forests results in a 30 to 40 mm change in streamflow (Bosch and Hewlett 1982); an increase following clearing and or decrease following afforestation. The corresponding changes for deciduous hardwood (poplar, oak) and scrub were ±25 mm and 10 mm respectively. In most afforested catchments, streamflow in predominantly generated from subsurface sources, and baseflow is the major component of the annual hydrograph. Thus, these catchment are an accurate measure of the effect of vegetation change on rechard. Direct evidence comes from studies which measured or reliably estimated recharge.

3.2.3.1 Australia

The most direct evidence linking vegetation change and recharge rates comes from the numerous studies in Western Australia and south-eastern Australia where replacement of natural woodland or forest with pastures has resulted in rising groundwater tables and extensive salinisation of soils (Williamson 1990).

In situations, shallow saline groundwater it is not possible to leach salts out of the soil profile as these move back to the soil surface by capillary rise. This secondary salinity occurs as saline seepages (798 000 ha), saline irrigated land (156 000 ha), and non-potable divertible surface water resources (1 326 million m^3 annually). Losses of production are estimated at A$214.6 million per year (Dumsday *et al.* 1989).

Affected areas typically have winter rainfall of 500-1200 mm per year and pan evaporation rates of 1200-1800 mm per year. An important factor is the highly permeable soils which result in minimal or no runoff. Recharge in deep profiles (10-30 m and deeper) varies markedly between different vegetation types and with land-use practices such as grazing (Table 3.7). Clearing of native mallee (shrub/tree savanna) in the Murray River basin has dramatically increased recharge from <0.1-0.2 mm per year to 3-30 mm per year (Barnett 1989). The recharge water from clearing over the last 50-80 years has yet to be fully reflected in the regional water table levels which will take 500-1000 years to equilibrate at higher levels. Further evidence comes from records of water table depths. Water tables in comparable landscape positions were up to 7 m lower under remnant vegetation than under transformed (cleared) areas in Wallatin Creek catchment (Western Australia) (McFarlane & George 1992). Water tables beneath eucalypt plantations (rainfall 462 mm, pan Et 1 503 mm) were 2-4 m lower than in adjacent pastures with the drawdown extending laterally about 20 m into the pasture and reaching 40 m in one case (Heuperman 1995). Tree lines in pastures can lower water tables in situations where the permeability of the saturated soil layers is relatively low (Travis & Heuperman 1994). On heavy soils (loam on low permeability clay) the drawdown was evident up to 10 m from the treeline.

Water movement through the rooting zone in vegetated semi-arid or arid areas can be delayed significantly by root extraction generated hydraulic gradients (Stephens 1994; see also Tyler & Walker 1994). Studies in deep sands in Western Australia found that wetting fronts took up to two weeks longer to reach the water table under pine plantations than under banksias and the drainage volume and duration (e.g. 88 vs 132 days) were reduced (Farrington & Bartle 1991). Drainage was also lower between trees than next to tree trunks, probably because of stem flow.

Table 3.7: Comparative rates of groundwater recharge under different vegetation types and following vegetation changes in the winter rainfall regions of Western and south-eastern Australia and the summer rainfall region in eastern Australia. (spha = stems per hectare)

Vegetation	Annual rainfall (mm)	Soil and water table depth (m)	Annual recharge (mm or % of rainfall)	Source and method
Banksia shrubland *Pinus radiata* plantation 2 200 spha 25 years old	775 (525-848 during study period)	Deep sands, 20 m	11% negligible	Sharma *et al.* 1983 (chloride method)
Banksia shrubland *Pinus radiata* plantation 750 spha 15 years old	775	Deep sands, 10 m	25% 7%	Sharma *et al.* 1983 (chloride method)
Grassland *Pinus radiata* plantation 24 years old, two sites	600-632	Deep sands over limestone, 7+m, 40 m	63 mm 0 mm	Holmes & Colville 1970a,b (soil moisture)
Natural eucalypt forest Perennial pasture Annual pasture un/grazed Perennial *Medicago* *Pinus pinaster* plantation	800-900	Deep sands, 15-20 m	34% 20-24% 20/21-43% 8% 11%	Carbon *et al.* 1982 (soil moisture)
Banksia woodland *Pinus pinaster* plantation 630 spha 18 years old	747 (PEt 1 800 mm)	Deep sand, 4-12 m	22-23% 15%	Farrington *et al.* 1989; Farrington & Bartle 1991 (chloride method, water balance)
Replacement of natural eucalypt forest by grassland	409 mean (339-494)	Colluvium & laterite on deeply weathered granite	0.4-1.0 mm increased to 10-25 mm	Salama *et al.* 1983a,b (chloride method, water balance)

Vegetation	Annual rainfall (mm)	Soil and water table depth (m)	Annual recharge (mm or % of rainfall)	Source and method
Replacement of natural eucalypt forest by grassland	800-820 1 100-1 220	Gravelly to sandy laterite on deeply weathered granite	10-30 mm increase 60 mm increase	38-53% cleared 100% cleared Peck & Willamson 1987 (piezometer water levels)
Eucalyptus grandis planted in grassland, 2-3 year old	1099 mean (739-963)	Podzolic loam	0-5 mm 2150 spha 17-23 mm 304 spha 74-79 mm 82 spha	Eastham *et al.* 1988 (neutron probe water content)
Natural woodland Pine plantation	800	Deep sand, 70-90 m	120 mm 245 mm young >4 mm mature	Sharma & Craig 1989 in Greenwood 1992
Eucalypt forest	1230	Loam on deeply weathered granodiorite	40-100 mm deep drainage	Talsma & Gardener 1986b
Banksia woodland	525-850	Deep sand, 70-90 m	34-149 mm, 10 m depth 65-80 mm, 18 m depth	Sharma *et al.* 1991 (soil moisture and moisture flux model)

Studies of the effects of reforestation in catchments in Western Australia (713 mm/yr; 80% in winter; pan Et 1 600 mm) found that it lowered water table levels; initially at an average depth of 3 m below ground level in sandy to gravelly clays and clays derived from weathered granite (Schofield & Bari 1991; Bari & Schofield 1992). Between 1980 and 1988 there was a net rise in the minimum and maximum groundwater levels of 1.8 m and 2.0 m, respectively, in deforested land under pasture. Reforestation resulted in a lowering, beginning 3-4 years after planting, of about 0.8 m per year. The absolute reduction of the minimum water table level was 5.5 m (7.3 m relative to pasture) and of the maximum level was 5.8 m (7.8 m relative). No indication is given of the storativities of the substrate water table or of the volume of water represented by these changes in water table level. At a storativity of 0.15 a head change of 0.8 m would represent 120 mm. Similar results have been reported for other catchments (Bell *et al.* 1990; Hookey 1987; Salama *et al.* 1993a,b).

3.2.3.2 Other areas

Conversion of cerrado (savanna) vegetation in Brazil to *Eucalyptus grandis* and *Pinus caribaea* plantations alters the water balance (Lima *et al.* 1990). With an annual rainfall of 1 121 mm, deep drainage (>1.8 m) under cerrado was 556 mm, under pines 450 mm and under eucalypts 326 mm. In the Amazon basin a change in cover from evergreen tropical forest to degraded pasture resulted in an increase of 370 mm in plant available soil water in the upper 8 m of the soil profile which could then seep into subsurface runoff or recharge groundwater (Nepstad *et al.* 1994).

Lysimeter studies in Holland showed a strong relationship between vegetation type, recharge and annual rainfall (Ter Hoeve 1978). Pine stands had the lowest recharge and the lowest rates of increase in recharge with increasing rainfall. Annual groundwater recharge under bare ground was 650 mm in a normal rainfall year compared with 854 mm in a year with 1.26 times the mean rainfall (Van Lanen 1978). Under hay (struweel) the corresponding values were 360 and 569, broadleaved forest 330 and 548 and pine forest 150 and 369 mm. In a sandy soil in Germany (661 mm/yr, PEt 625 mm) the mean groundwater recharge was: pine forest 141 mm/yr, grassland 218 mm/yr, arable land 250 mm/yr, vegetables 280 mm/yr. Under similar soil physical conditions, drainage water under asparagus passes through the 10 m unsaturated soil profile in only 2-3 years, whereas under pine forest it takes more than 6 years.

Infiltration rates are high where there is no overland flow on undisturbed sites in the arid mid-west USA but where vegetation is degraded or absent 40-60% of the rainfall becomes surface flow (Croft 1950). Annual evaporation was about 279 mm for aspens with a herbaceous understorey, 203 mm with aspens removed and 76 mm from bare ground. Aspen roots penetrated the soil to at least 1.8 m. Thus removing aspens will increase both groundwater recharge and runoff.

Under a rainfall of 340 mm/yr, recharge can range from 10 to >50% of rainfall with bare sandy soils, but for exposed silt loams there was no recharge because in these lower permeability soils the subsurface water does not penetrate beyond the point where hydraulic gradients can raise it to the surface to evaporate (Gee *et al.* 1994). Where there was perennial shrub vegetation there was greater infiltration but the plants depleted the water within their rooting depth (0.4-0.8 mm/day) resulting in no groundwater recharge. Under winter annual grasses the profile remained moister and there was recharge in coarse sandy soils.

Groundwater recharge occurs even in arid regions (precipitation <250 mm/yr) where average annual precipitation/evaporation is <0.5, but it usually only occurs in wetter than average years or in areas with winter/spring rainfall where precipitation occurs while evaporation is low (Stephens 1994).

In the Negev desert, Israel, (100-210 mm winter rainfall) recharge is about 70% on sand dunes with no perennial vegetation. In similar areas with deep rooted vegetation (1.5 m) there may be no recharge (Issar *et al.* 1984). In limestone areas recharge is about 2%, primarily through gravel beds in rivers under flood conditions. Other estimates of recharge range from 7.6 to 25% under desert sand dune conditions and about 1% for limestones. Rainfall events of less than 5 mm in dune systems with 40% annual vegetation cover are unlikely to recharge groundwater.

In vegetation with a mixture of trees and grassland, water balance differs in open areas and under tree clumps. In mediterranean oak-grassland woodlands (savanna) in Spain, the water use of oak trees was about 590 mm/yr compared with 400 mm/yr in the annual grasslands (Joffre & Rambal 1988, 1993). Generally in mediterranean shrublands runoff on recharge only occur once rainfall exceeds 550-600 mm. Overall, evaporation from these open mediterranean woodlands is intermediate between that of grasslands and deciduous forest of north-eastern North America (Valentini *et al.* 1991; Dawson 1993c).

Removal of mesquite (*Prosopis glandulosa*) in savanna (rainfall 682 mm/yr) increased evaporation by 2.4%, decreased runoff by 3.0% and increased deep drainage by 0.6% (Heitschmidt & Dowhower 1991). This was primarily due the higher productivity of the formerly under-canopy grassland when mesquite was removed. Another study in an area with 529-769 mm/yr rainfall during the study period (long term rainfall 646 mm/yr) found the following (Carlson *et al.* 1990; Table 3.8):

Table 3.8: A comparison of the impacts of different vegetation types on evaporation, runoff and recharge (after Carlson *et al.* 1990).

Vegetation	Evaporation (% of rainfall)	Runoff (% of rainfall)	Deep drainage (% of rainfall reaching 3.05 m)
Prosopis & herbs	95	4.6	0.4
Herbs	97.4	1.6	1.0
Bare ground	84.4	14.3	1.3

3.2.3.3 South Africa

Deep percolation under savanna was measured with lysimeters in the Pretoria area (Theron 1964, cited by O'Connor 1985). Under fallow (unplanted, previously cultivated land) 22% of the annual rainfall leached to >1.68 m every year; under crops (maize) 11% percolated past 1.22 m; under natural grassland 11% reached 0.61, 6% 0.91 and 4% 1.22 m. The volume was directly proportional to the rainfall with percolation under grassland being effectively zero in dry years. Seasonal recharge of groundwater and the unsaturated zone was studied in three sub-habitats of *Burkea* savanna in deep sandy soils at Nylsvley with a variable rainfall averaging 530 mm per year (Moore *et al.* 1982). A soil depth of 0.3 m will retain ±25 mm and 0.45 m will retain ±35 mm. *Burkea* maintains roots throughout the accessible profile. There was therefore a large potential for drainage of water beyond the rooting zone. In contrast, modelling by Scholes and Walker (1993) suggests that this site (Nylsvley) wetting fronts after rainfall events rarely reach further than 1 m depth because the soil field capacity is equivalent to the volume from typical rainfall events and sequences. Evaporation is thus equivalent to rainfall, with about one third being lost via transpiration. Drainage of water to deeper levels (the water table is at 20 m) must occur only when exceptional rainfall events and sequences occur, provided that water is not moving through the profile after lesser rainfall events in macro-pores or other channels. The sub-habitats characterised by the grass *Eragrostis pallens* and the shrub *Ochna pulchra* exhibited drying out only in the upper 0.6 m of the profile, leaving a well watered profile below this depth. The upper 0.3 m under *Eragrostis* was the most affected with relatively less drying out of the 0.3-0.6 m layer. Under *Ochna* the profile was dried out to 0.6 m with no extraction below 0.9 m. The sub-habitat with *Grewia flavescens* showed roots extracting water throughout the profile (1.4 m+), and slower recharge to lower maximum moisture levels after rainfall events. Drainage beyond the rooting zone therefore seems unlikely in the *Grewia* sub-habitat.

Evaporation from central Orange Free State (OFS) grassland varied according to its successional stage (Snyman 1988). The climax stage showed the highest evaporation with a mean of 615 mm/yr (mean annual rainfall 550 mm/yr). Evaporation from bare soil averaged only 467 mm/yr. The rate of infiltration varies with grassland condition and rainfall. (Table 3.9)

Table 3.9: Evapotranspiration from different stages of central OFS grassland based on lysimeters (Snyman 1988). {Evaporation presumably exceeds rainfall over the period of measurement by drawing on water stored in the soil profile.}

Period	Rainfall (mm)	Evapotranspiration			Evaporation
		climax (70% *Themeda triandra*, 30% *Digitaria eriantha*)	**subclimax** (50% *Eragrostis lehmanniana*, 25% *E. chloromelas*, 25% *Sporobolus fimbriatus*)	**pioneer** (60% *Aristida congesta*, 20% *Cynodon hirsutus*, 20% *Tragus koelerioides*)	**bare soil**
1979/80	466.5	626.7	623.6	530.3	358.5
1980/81	724.5	761.5	729.8	663.0	564.1
1981/82	669.7	685.0	689.3	659.6	609.1
1982/83	330.9	386.6	371.6	375.7	336.8
Mean	547.9	615.0	603.6	557.2	467.1

3.2.3.4 Summary

Can changes in vegetation cover or vegetation management alter the depth and recharge of groundwater?

There is strong evidence that changes in vegetation alter both recharge rates and water table depths. Most of the evidence comes from Western and south-eastern Australia which share the following features (a) highly permeable soil profiles, at least for the upper few metres, so that surface runoff is negligible, (b) winter or bimodal rainfall, and (c) deep rooted forest vegetation which used a large proportion of the available soil water so that deforestation led to increasing the recharge rates by 1-2 orders of magnitude. Studies show water tables to be lowered by reforestation with depressed water tables around stands of phreatophytes. Infiltration rates are shown to be affected by different vegetation types. The applicability of these findings to southern African situations needs to be studied.

South African studies have focussed on the depth of infiltration in the unsaturated zone under different vegetation communities. Studies of the long term impact of changing vegetation on water tables have not been carried out, particularly in areas with shallow water tables, e.g. coastal dunes. The available evidence for South Africa suggests that in semi-arid and arid savanna and grasslands, groundwater recharge in dry years will be negligible, and wet periods are needed to produce significant groundwater recharge. Recharge is likely to occur regularly (approximately annually) only in humid areas.

3.3 Summary

The first part of the literature review comprised a synopsis of the effects of plants on the processes involved in the passage of water from rainfall to groundwater. Interception involves the capture of precipitation on plant surfaces and litter. Intercepted rainfall may then evaporate or reach the soil by stem flow, throughfall or percolation through the litter. Absolute amounts are highly variable, determined by both climatic factors (e.g rainfall duration and intensity, evaporative demand) and plant related factors (e.g. leaf area, leaf form). In general, interception losses will be highest in areas with low intensity rainfall and high evaporative demand, and for plants with dense canopies (a high leaf-area index), rough bark and deep litter layers. On average interception accounts for 5- 20% of annual precipitation but it can be much higher. A semi-quantitative summary of data for West African savanna systems is given by Breman and Kessler (1995; Table 3.10). Stemflow may be important but South African studies are needed to examine the extent to which stemflow can feed into root channels and recharge groundwater directly. Several studies have shown that plants also contribute to infiltration, and thus to recharge, by improving soil texture and hydraulic conductivity.

The second part of the review addressed three key questions on (a) the depths of plant root systems, especially of phreatophytes; (b) the impacts of changes in water tables on plants; and (c) the impacts of vegetation changes on groundwater resources:

Depth of Rooting.
(a) Information on the depths of root systems and plant use of groundwater suggests that the generalisation that plant roots are shallow (max 1-2 m) is too simplistic. The majority of the root mass is undoubtedly in the upper soil layers but many species, especially woody plants, are potentially deep rooted (>2.0 m). Although only a few roots may reach groundwater, these deep roots appear to be specialised for lifting water from considerable depths and such plants may have a substantial impact on groundwater resources (Table 3.10). Phreatophytes are a heterogenous group ranging from species that are (a) highly adaptable, able to tap groundwater at great depths and moderately resilient to moisture stress, to (b) shallow rooted species with little or no resistance to moisture stress. Most phreatophytes maintain high transpiration rates and often make exclusive use of groundwater even where other superficial sources are available.

The response of vegetation to fluctuating water tables.
(b) Changes in water table levels, especially lowering, can have a significant impact on both riparian and wetland communities with the extent of the impact depending, at least partly, on the rate of change. Community responses can be subtle and there may also be substantial lags in the responses.

Effects on groundwater.
(c) Similarly, changes in vegetation alter both recharge rates and water table depths. In general shorter vegetation and seasonal crops have lower transpiration rates than tall vegetation which results in potentially greater recharge. Where groundwater is within the rooting zone of vegetation, groundwater may be used directly to feed transpiration, thus lower water table levels.

Table 3.10: The maximum effects of various processes associated with woody plants in the Sahel and Sudan zones on water availability for primary production of a mixed vegetation, considering the effects in the canopy area and canopy cover in the vegetation as in the pre-drought situation, in comparison to a vegetation without woody plants. After Breman & Kessler (1995).

Process	**Effect on water availability to vegetation**	**Zone**	
		Rainfall: 150-600 mm canopy cover: 2-20% (Sahel zones)	**Rainfall: 600-1200 mm canopy cover: 15-35% (Sudan zones)**
Rainfall interception [a]	Losses by evaporation from foliage Gains by net throughfall exceeding gross rainfall under woody canopy	- 0	- 0
Stemflow [b]	Redistribution to deep soil around stem [c]	+	++
Improved soil structure [b]	Increased water infiltration leading to reduced run-off [c]	+	+++
Increased soil organic matter content [b]	Increased soil moisture retention capacity [c]	0	+
Transpiration by woody plants [a]	Decrease of water use efficiency [c]	-	-
Micro-climatic changes [b]	Reduced PET, relative increase of transpiration of water use efficiency	+	+
Hydraulic lift [b]	Less percolation losses	0	0
Uptake by deep roots [a]	Less percolation losses [c]	+	+++

0 = negligible effects
+, ++, +++ = positive effects on water availability of 10-50, 50-100 and > 100 $mm\ yr^{-1}$ respectively.
- = negative effects on water availability of < 50 $mm\ yr^{-1}$.
[a] Processes that improve water availability for the woody plant only.
[b] Processes that might improve water availability for the herb layer.
[c] Effects decreasing rapidly through exploitation of the woody species.

4. SOUTHERN AFRICAN CASE STUDIES: SYNOPSIS OF PUBLISHED AND ANECDOTAL INFORMATION

Southern African cases involving an interaction between vegetation and groundwater are reviewed in this section. Case studies come from South Africa, Botswana and Namibia. The initial part of this review is organised by the aquifer types as described in Section 2.1.

4.1 Vegetation - groundwater interactions in hard rock (secondary aquifers).

4.1.1 *The hydrological effects of afforestation* (Nanni 1970; Bosch 1980; Hewlett and Bosch 1984; Van Wyk 1987; Bosch and Smith 1989; Scott and Smith 1997)

The large body of South African afforestation experiments is our best measure of the effects of a land cover change on hydrology and also, indirectly, groundwater. The afforested catchments are in high rainfall areas (>700 mm/year), mostly hilly to rugged, and with localised groundwater systems, feeding perennial streams. The yield of the catchments is dominated by baseflow (i.e. groundwater discharge). The response of the catchments to storms is low (storm response ratios are usually below 10%, and always below 20% of large storms), though the annual response of the catchments is high - typically above 20% of annual rainfall. Forestry affects all parts of the annual hydrograph in a similar way; in other words afforestation causes a markedly reduced groundwater discharge.

This impact of forests is thought to be predominantly through increased transpiration (hence the high productivity of the tree crops) rather than through increased interception losses (Scott and Lesch 1997). Deep rooting of trees is known to occur (Section 4.1.1.1 below), but trees can have a large effect on water balance even where root depths are not particularly great. The root systems may affect groundwater by decreasing recharge through extracting water from the unsaturated zone and creating additional storage capacity in the unsaturated zone, without there being a direct abstraction from groundwater.

4.1.1.1 Deep rooting by eucalypts

Research on plant water use and stress of eucalypt trees in plantations has been performed by Dye and colleagues in Mpumalanga (Dye 1996). In a situation where they were able to root deeply, in this case specifically on deeply weathered Nelspruit granite, trees were denied recharge from rainfall by means of plastic sheeting over the ground. The trees showed little stress relative to control trees outside the covered area, and monitoring of soil wetness by means of neutron probe measurements indicated that water was being extracted from deep unsaturated soil or saprolite: three year old trees were vigorously extracting water from depths down to 10 m, while ten year old trees abstracted water largely from below the maximum measured depth of 8 m.

This unique study shows:

- that eucalypts had established roots to great depths early in the rotation;
- this was the case even before the roots were denied recharge from rainfall;
- that eucalypts can be expected to root as deeply as the profile allows, regardless of a high rainfall; and
- these roots alone were sufficient to maintain an adequate water supply to the trees.

The results imply that where there is a deep soil, or deeply fractured or decomposed rock the vigorous eucalypts can have a large impact on groundwater without necessarily having access to saturated zone water.

Afforestation of the whole of the grassed Mokobulaana research catchment, Mpumalanga Province, catchment with *Eucaluptus grandis* led to the stream drying up after 9 years. Although the trees were clearfelled at an age of 16 years, streamflow did not return to near normal until a further five years later; roughly 630 mm of rainfall being needed, over and above evaporative losses, to replenish unsaturated zone water stores and restore normal streamflow generation (Scott and Lesch 1997). The soils of this catchment are agriculturally very shallow, "just a few centimetres" (Nanni 1971), but the shale substrate (Daspoort Shales of the Pretoria Group) is broken and contains water reserves to 45 m below the surface without being saturated (Dye and Poulter 1991).

4.1.1.2 The geohydrology of a wattle plantation (Kok 1976)

The geology of this wattle research farm north of Pietermaritzburg is predominantly shales of Lower Ecca with dolerite intrusions. Dwyka shale and tillite occurs in the southeastern corner of the farm and underlies the other formations. The bedrock is decomposed to 1 - 15 m, with dolerite typically weathered to 3 m of its 15 m thickness. The shale is jointed. The contact between Ecca shales and dolerite is baked and forms an aquifer. Rainfall averaged 909 mm/yr from 1952 to 1971, predominantly falling between October and April.

The farm is hilly with local relief of 150 m, and drained by ephemeral tributaries of the Rietspruit. There are five springs on the farm that discharge on the contact between the shale and dolerite sheet. One spring was measured for a year and recharge was calculated to be around 7% of rainfall (yield of 33 000 m^3 from an estimated catchment of 500 000 m^2). A recharge figure of around 10% could have been expected (Kok 1976), and perhaps the presence of the trees had reduced recharge by the difference (Kok 1976). Springs show a clear response to rainfall, with a lag of 1-2 months.

Hydrographs of borehole rest water levels showed variations of several metres prior to clearfelling. Groundwater levels rose after clearfelling but showed reduced recharge peaks as the wattles grew, until no recharge was evident at 5 to 8 years after planting. Kok concluded that mature wattle plantations at Bloemendal intercept or transpire all of an expected annual recharge of 10% of annual rainfall (900 mm).

4.1.2 *Bush clearing in North West and Northern Provinces* (Vegter 1993)

Studies in the bushveld areas in the Thabazimbi and Waterberg districts of North West and Northern Provinces, indicate that clearing of bush has enhanced groundwater recharge into granitic and crystalline metamorphic rock formations. The piezometric surface is far below the surface (40 - 80 m), and the benefits of bush clearing appear to arise from reduced interception and transpiration of water out of the shallow soil profile, i.e. an increased recharge effect. In the Thabazimbi area the water table rose by about 20 m over a 30 year period. Recharge appears to occur in wetter years only.

4.1.3 *De Aar's Water Supply: possible impacts on the productivity of adjacent agricultural land* (LWSK 1989; Vegter 1992)

Farmers in the vicinity of De Aar's municipal water supply schemes particularly those in the Brak River valley, south of the Burgerville scheme, complained of veld degradation that they blamed on falling water tables. In the Brak River valley, which is at a lower elevation than the Burgerville Valley, the water levels are from one to several metres below the surface and have a natural range of around 2 m. On the plains above the valley water levels are between 3 - 6 m below ground level, with a natural range in rest level of 4 m. In some of the municipal well-fields water levels during the drought of the 1980s had fallen to 7 m below the surface. The aquifers are of three sorts, namely, (i) weathered Karoo shales and sandstones, with dolerite contacts that enhance water bearing capacity, (ii) alluvial deposits along two branches of the Brak River, and (iii) a combination of the above aquifers.

The expert opinion was that it was highly unlikely that groundwater exploitation had negatively affected veld condition,

- given that the groundwater gradients showed no apparent connection between the systems involved, and
- as most karroo plants are considered to be shallow rooted and not dependant on a groundwater source (other than obviously phreatic vegetation). (but see section 3.2.1.4)

4.1.4 *Kathu Impact Study: Kathu Forest, near Sishen, Northern Cape Province*

There are four monitored boreholes in the vicinity of the Kathu Forest, a woodland of *Acacia erioloba* trees. A single aquifer appears to underlie the forest. Depth to water table generally ranges between 7 and 15 m (maximum of 20 m at a single borehole in 1975). Thus it is quite feasible that the forest trees are at least partially dependent on abstracting water from the Kathu Aquifer.

A desk-top investigation was carried out to ascertain whether draw down of the water table caused by pumping in the Kathu - Sishen Well Field (supplying groundwater to nearby Kathu Township) is resulting in the death of camel thorn trees (*Acacia erioloba*) in the Kathu Forest.

The study of borehole records from the area shows that (Van Wyk 1997):

- there is more water in the aquifer (higher rest water levels) now than before 1974 when monitoring commenced;
- rest water levels have fallen by only 2.5 m since 1990, well within the normal range as measured in the past;
- pumping in the Kathu Well Field is probably more than compensated for by heavy irrigation in the Kathu Township which is supplied with water from the Sishen Mine Aquifer (a separate aquifer); and
- it is estimated that at roughly 60% increased abstraction rates during a series of ten low rainfall years, the Kathu Aquifer would not experience draw downs in excess of natural variation.

However, under such a pumping regime, the duration of drawdown would be longer - vegetation may be resistant to short periods of water stress that occur in the natural water cycle, but not to progressively declining groundwater accessibility. Leaching of irrigation and domestic water from the Kathu Village can be expected to have negative water quality impacts on the aquifer.

4.1.5. *Miscellaneous observations in Northern KwaZulu-Natal*

Van Wyk (1963) reported that significant recharge in the Lebombo volcanics only takes place in exceptionally wet spells. From 1943 to 1957 groundwater levels in Northern Zululand savanna fell, even without pumping, i.e. declines were caused by lowveld trees alone. In 1957 high rainfall over a short period recharged water levels to 1943 levels.

4.1.6 *Grootgeluk Coal Mine, near Ellisras, NW Province*

Drilling in Clarens Sandstone in the semi-arid North West Province, showed root fragments from depths of 9 or 10 m. (Dreyer[2], personal communication 1996)

4.1.7 *Mr Koos Viviers (Geohydrologist with Eskom Mining)*

Mr Viviers comments that in bushveld country one can use aerial photographs to pick up forest patches and use these in the search for water sources. His contention is that forests occur along fault lines because of the ease of access by trees to water that rises up such zones toward the surface. It can be argued that there are other plausible hypotheses to explain the presence of trees on such geological features.

---

[2] Mr Klaris Dreyer. Chief Geologist, Grootgeluk Coal Mine, Ellisras (xxx)

4.1.8 *WT (Jack) Bennett[3], Bennett Drilling, Pretoria* (personal communication 1997)

Mr Bennett is a private driller with personal experience in drilling in around Gauteng, Northern Province and Swaziland. He reports that it is widely known that good groundwater seems to be associated with karree trees (*Rhus lancea* and other *Rhus* species), though these may not necessarily be growing in likely or obvious points for groundwater. He has personal experience of striking good water deep beneath karree trees after unsuccessful holes had been drilled in more obvious points on the same farm.

Also, an obvious row of healthy trees may indicate a weathered zone or fracture in the rock where one is more likely to drill a successful borehole.

4.1.9 ***Richmond Karroo, "Karoo word droog gepomp" Landbouweekblad,*** 5: (July 1985)
Sound veld management and reduced stocking together with anti-erosion structures to retard surface runoff, have led to stable streams and higher water tables (as indicated by "kuile" holding water during droughts).

4.2 Vegetation - groundwater interactions on coastal aquifers

Some of the largest primary aquifers in South Africa are those formed by recent sand deposits along the coasts. Depths to water tables are typically low and wetland systems may be associated with the shallow fluctuating water tables.

4.2.1 *Rising water tables and poor drainage in Cape Flats township developments* (van Niekerk[4], personal communication 1997)

High water tables and poor drainage problems are associated with housing at Blue Downs housing development which is 20-30 000 erven in extent (includes Delft, Eerste River, Blackheath industrial area). These problems have been blamed on the clearing of vegetation that preceded the housing project. Prior to development for housing the area was covered in dense thicket of Port Jackson willow and rooikrans (*Acacia saligna* and *A. cyclops*, respectively) and there were also well developed stands of eucalypts. Initially (first couple of years) there were no problems, and none were anticipated because of the sandy soils. But there is now surface ponding in areas thought to be perched water tables.

The water table was previously 2-3 m below surface but is now close to or above the surface in lower lying areas. Low permeability layers near the surface are thought to be supporting perched

---

[3] Mr W T Bennett, Bennett Drilling, Pretoria (012 545xxx)

[4] Mr Andre van Niekerk, Engineer Blue Downs District, Stellenbosch office of Cape Metropolitan Council (012 - 8875111).

water tables. Springs have developed within the housing development, and the floors of some houses have even leaked. Detention ponds that were designed to temporarily hold storm water, and to double as sports fields, are now perennially inundated, and the standing water is causing health problems.

4.2.2 *Timber Plantations on the Zululand coastal plain*

The quaternary deposits, largely sands, on the broad and flat northern Zululand coastal plain also form an extensive, generally unconfined aquifer. One of the primary land uses on this coastal flat is forestry, with both pines and eucalypts being grown on short rotations for pulp. The few studies that have been carried out in this region have shown that the impact of the plantations is comparable to that of plantations on the uplands (Rawlins and Kelbe 1991). Root excavation and isotope studies have shown that the roots of the trees are capable of extending down to the capillary fringe of the water table to ensure access to a reliable source of water (Haigh 1966; Scott 1993; Midgley *et al.* 1994).

The fact that trees can abstract directly from the groundwater means that they may have a broader impact than simply in the area where they are planted, and that they are much less likely to suffer seasonal water stress than if they were to rely on rainfall and unsaturated zone water alone. The potential impact of existing and additional plantations on the coastal aquifer has been modelled using INTERSAT, a three dimensional model that is primarily a groundwater model (Rawlins and Kelbe 1991; Kelbe *et al.* 1995) but set up to run with a separate daily recharge model that determines net rainfall and keeps track of storage deficits in the soil. Running this model under natural and afforested scenarios for the Western and Eastern Shores of Lake St Lucia on the full available rainfall record, it was estimated that the existing extent of plantations would have reduced groundwater discharge to the lake from the Eastern and Western Shores by 26% and 29% respectively (Kelbe *et al.* 1995).

The ACRU model was modified to model the extraction of water from a deep soil as well as abstraction by roots of water from the saturated zone. Simulations of groundwater levels beneath a 100 ha eucalypt plantation showed a dramatic draw down over a ten year period, the depth of which would be determined by the assumed maximum rooting depth of the trees (Kienzle and Schulze 1992).

4.2.3 *Atlantis Aquifer*

This aquifer has been well studied by the CSIR for groundwater management purposes. It is comprised mainly of quartzitic sands. The water table is normally 4 - 7 mbgl and the aquifer has a maximum saturated thickness of 25 m. Aquifer permeability is around 20 m/day. It is estimated that recharge beneath fynbos (the native vegetation) is around 8% of rainfall (~40 mm/yr), while under bare sand (dunes) recharge is estimated to range between 30 - 60% of annual rainfall (210 mm/yr). It is expected that recharge beneath the dense stands of vigorous, invading acacias will be lower than under fynbos, 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 *Acacia saligna* cover (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 the different sources of nitrate in the groundwater to be natural soil biota and vegetation for the control area and sewage sludge in the field. The acacia were infected with rust fungus and dying off in the control area, providing a significant biomass source with little or no nitrate uptake from the sandy soil.

4.2.4 *Blouvlei*

The unconfined, sandy, coastal aquifer at Blouvlei, north of Cape Town, is similar to the Atlantis Aquifer. A field study and numerical modelling of groundwater and ephemeral and permanent vleis around Blouvlei was carried out by the CSIR (Sililo 1996). These showed the main hydrogeologic mechanism for water loss in the area was evapotranspiration from *Acacia saligna*. Urban development of the area and the removal of vegetation would therefore result in a higher water table.

4.2.5 *Miscellaneous observations*

Roots were found in boreholes at 24 m in Acocks' types Tropical Lowveld & Coastal Forest and Thornveld (presumably the unconsolidated recent sands of the coastal plan). (Van Wyk 1963) Such reports may only indicate that a borehold makes it possible for roots to explore to greater depths.

Clearing of low savanna and thicket to permit cultivation for pineapple production in the False Bay area (old sand dunes west of Lake St Lucia) caused water tables to rise by 11 m (from 12 m to 1 m below surface). (Van Wyk 1963)

4.3 Vegetation - groundwater interactions on Kalahari sands

Kalahari deposits cover an extensive area of Southern Africa, in the Northern Cape and Northern Province. These deposits, mainly unconsolidated sands, permit deep penetration by roots because of the limited occurrence of physical barriers. In arid areas of Kalahari sands some of the deepest root occurrences in Southern Africa have been recorded. In this situation the trees have both the need (because of the arid climate) and the ability (because of the depth of the unconsolidated deposits) to root deeply.

4.3.1 *The observations of Dr Chris Jennings:* (Jennings 1974)

Dr Jennings made many observations on rooting behaviour of trees in Botswana, and also of the associations between trees and groundwater. Fine roots were found in fissured rock in mine shafts east of the Makgadikgadi Pans at depths of 30 and 45 m below the ground surface. The record of the deepest roots, perhaps in the world, comes from Phuduhudu in central Botswana from the inside of a disused borehole. The borehole was cased with unperforated casing to a depth of 68 m and water was at 141 m below the surface. The roots must have been below the 68 m, and the only tree of any size in the vicinity was a *Boscia albitrunca*. Other instances of deep roots were in a borehole with solid casing to 30 m and perforated casing to 78.6 m and the water at 97.5 m. (Again such observations to not prove that roots would be that deep were it not for the borehole.)

Phreatophytes along the rivers in Botswana (Okavango Swamp, Thamalakane, Nghabe and Bobeti Rivers) were noted to have dense root mats in the saturated sands. Linear formations of trees typically indicate dykes, joints or fault planes, which may provide better soil or water for deep rooted plants. Jennings cites Martin (1961) as stating that rows of *Acacia erioloba* (formerly *Acacia giraffe*) in eastern Namibia are indicators of deeper buried channels with coarse sediments and more water. In the Ghanzi district of Botswana *Combretum imberbe* (hardekool) appears to indicate fresh shallow groundwater; while west of Tsienyane *Acacia erioloba* and in the Nata Ranches area the palm (Hyphaene probably *benguelensis*) indicates saline groundwater.

4.4 Vegetation - groundwater interactions on alluvial aquifers

In a Southern African context this type of aquifer exhibits the most obvious of the groundwater - vegetation interactions. Alluvial aquifers are fairly common occupying the lower reaches of many Western Cape and KwaZulu-Natal Rivers, the Sand River, Northern Province and the Crocodile River, North West Province, but in arid to semi-arid areas are likely to be the primary reliable water source. They typically have a dependent riverine vegetation. These cases, because of the importance of the water resource are also the best studied cases in Southern Africa. The best known examples are the Kuiseb River in Namibia and the Limpopo River Valley near the junction with the Sashe River.

4.4.1 *Venetia Diamond Mine on the Limpopo: monitored exploitation scheme*

De Beers Consolidated Diamond Mines, in developing the water supply scheme for the Venetia Mine just south of the Limpopo Valley, came to an agreement with provincial nature conservation authorities whereby groundwater abstraction would be monitored, and exploitation would be kept within agreed operating rules: minimum levels of 4 m below the October 1989 water level on the farm Greefswald and a voluntary constraint of 4 m below the August 1991 level on the neighbouring farm Schroda. The underlying principle is that the riparian trees are dependent on the alluvial aquifer, and pumping should not put the trees at risk beyond stresses imposed typically by the environment. The common riverine tree *Croton megalobotrys* was chosen as the indicator for several reasons, primarily as it is inherently sensitive and responds rapidly to changes in soil water.

The water supply scheme consists of two well-fields along the southern bank of the Limpopo river, one on the farm Greefswald and the other on the adjacent farm Schroda. There are 33 groundwater level recording points on Greefswald and 13 on Schroda. Control sites and the wellfields are monitored. Other aspects monitored are water level in the Limpopo when it flows, rainfall, and plant stress in riverine vegetation. Regular monitoring reports are produced by both the mining company and the nature conservation authorities. It is not clear whether the operating rules were derived as a result of research, or whether they are simply a starting point that may be adapted in response to monitoring results. This case is unique in that exploitation of groundwater is linked to environmental modelling. In the long term, the monitoring results are likely to provide information on the relationship between the riparian trees and groundwater.

4.4.2 *Limpopo River and Irrigation Demand*

Between Venetia and Messina on the Limpopo River heavy exploitation of the alluvial aquifer for irrigation purposes resulted in extensive mortality in riparian vegetation. (E. Braune[5], personal communication 1997)

4.4.3 *Survival of the riparian woodland downstream of the Oanob dam* (Du Plessis[6])

The Oanob Dam on the Oanob River was completed in 1990 to improve water supply to Rehoboth. There are two aquifers below the dam previously used to supply water to Rehoboth. The aquifers are known as the upstream and downstream aquifers. The upstream aquifer begins approximately 5.5 km downstream of the dam and underlies the next 6 km, while the downstream aquifer underlies the next 16 km of the river. The two aquifers are partly separated by a geological barrier 11 m below surface. If the water level in the upstream aquifer rises to less than 11 m below surface the upstream aquifer leaks into the downstream aquifer.

The Department of Water Affairs of Namibia were concerned about the effect the dam would have on the riparian trees that were associated with the aquifers. The main tree species on the banks of the Oanob River is *Acacia erioloba* while *A. karroo* and *Ziziphus mucronata* are much less abundant. An investigation using stable isotopes confirmed that the *A. erioloba* trees tapped the alluvial aquifer in the buried river channel (sapwood water had the same isotopic signature as the groundwater). The downstream aquifers are monitored by Namibian Water Affairs, and approximately $2.5 \times 10^6 m^3$ water was released from the dam in June 1994 to recharge the aquifers, and maintain the dependent riparian trees.

4.4.4 *Kuiseb River in Namibia*

This river has several tributaries that rise in the Khomas Hochland, south of Windhoek. The

[5] Mr Eberhard Braune, Director, Geohydrology Division, Department of Water Affairs and Forestry

[6] Mr N P Du Plessis, Namibian Department of Water Affairs, Windhoek

river flows westward down the escarpment, through a steep canyon, then across the Namib desert to a delta just south of Walvis Bay and roughly 10 km from the coast. Although essentially a dry river that last flowed to its estuary in 1961 (Braune 1991), floods do reach to around Gobabeb in most years.

Surface water in the channel usually lasts for a few days during which time the alluvial aquifers are recharged. The alluvial aquifer of the lower Kuiseb River supports a riverine fringe of woodland consisting of four main species, namely *albida. Acacia Faidherbia. erioloba, Euclea pseudabenus* and *Tamarix usneoides*, decreasing in size and proximity to the river in approximately that order. This woodland supplies vital forage to many desert animals during times of extended drought (Bate and Walker 1993).

Exploitation of the aquifer to supply water to the town of Walvis Bay has seen water rest levels drop by 8 m, over a twenty year period, from the highest recorded levels in 1974 (Bekker 1992) and has the potential to deny the riparian trees their access to groundwater.

4.4.5 *Buffels River, Northern Cape Province: Okiep Copper Mine, near Springbok*

Riparian scrub and trees (*Acacia karroo*) were cleared on a programmed basis to reduce the evaporative losses from the alluvial aquifer that was used for water supply. The entire mining activity was dependent on this water resource for about 25 years and, in view of the presence of fluctuations in rest water levels, it was assumed the trees were responsible for direct abstractions from the alluvial aquifer. The mine now gets water from the Orange River, and is no longer dependent on the Buffels River aquifer.

4.5 Geo-technical issues related to vegetation

The following cases illustrate the problems that can result from the wetting of expansive soils caused by the sudden clearing of vegetation with a high water use. It is not clear that these cases are strictly related to groundwater: the wetting of expansive soils may be take place without the associated rise in piezometric surfaces. It has now become general wisdom in South African geo-technics that changes of vegetation can lead to re-wetting of potentially expansive soils, with the result that the soils may heave.

4.5.1 *Lethabo Power Station and other Highveld construction sites*

Blight (1987) documents three cases on the Highveld where the recovery of depressed water tables followed the clearing of eucalypts from sites that were to be developed. Water tables had been drawn down, relative to surrounding agricultural areas by 10, 19 and 20+ m. The soils on these sites may swell as a result of a decrease in effective stress and because they are expansive. One such site was the Lethabo Power Station south-east of Vereeniging. To avoid problems resulting from the recovery of the water table, piles had to be sheathed against lift. Though not unanticipated this added considerably to the overall construction costs (Dittmer[7], personal communication 1996).

4.5.2 *Pilkington Glass Factory, Springs* (Hammond[8], personal communication 1996)

In preparing the construction site for this plant a small eucalypt plantation was clearfelled. The high transpiration rate of the eucalypts are thought to have depressed the groundwater beneath the plantation and desiccated the soils above the water table. Following clearfelling of the trees, the water table recovered and the soils beneath the factory became wetter. The change in wetness of the soils caused them to swell, causing heave. Heave also occurred as a result of the change in effective stress caused by the rise of the water table. The amount of heave experienced was not large but resulted from a small percentage swell over a large depth and in soils that were not particularly expansive.

The float glass process used at the plant requires very precise levels, and consequently the heaves would not have been noticed. A large court case resulted, and a full investigation was conducted by Soil Mechanics Ltd (UK) on behalf of Pilkingtons. Full documentation is available from Soil Mechanics and Arup & Co., Johannesburg.

4.6 Mortality of trees due to changes in hydrogeology

Ward[9] (personal communication 1996) studying mortality in acacia trees in Israel, lists the causes as (i) exploitation of groundwater for agriculture, and (ii) roads without regular culverts that cut off ephemeral channels, and thereby reduce the water supply to the downslope side of the road. He stresses at the same time that acacias are pioneers and will often be of a single age (as a result of mass recruitment following disturbance), so that mortality must be studied relative to recruitment, or bearing in mind the possible circumstances (disturbance, over-grazing) under which mass recruitment might have occurred, and whether such opportunities still exist.

4.6.1 *'Anabome' National Monument, Potgietersrust*

The national monument, "Die Anabome", a grove of *Faidherbia albida* trees (reputedly the largest indigenous trees on the highveld), at Tin Mine (near Potgietersrust) is dying. This has been put down to the fact that eucalypts have been planted on surrounding land (presumably lowering the water table and causing these trees water stress).

---

[7] Colin Dittmer, Arup & Co., Consulting Engineers, Johannesburg.

[8] Tony Hammond, Geotechnics Africa cc, Johannesburg.

[9] Dr David Ward, Director, Ramon Science Centre, Institute for Desert Research, Ben Gurion University, Sede Boqer 84990, Israel.

4.7 Vegetation and mine water

A recent study for the WRC (Versfeld *et al.* 1997 investigated the use of vegetation to assist in the control of water in mining environments, including attempts to minimise acid mine drainage by using trees to reduce percolation of water through soils overlying mined sites or flowing away from slimes dumps. Measurements on a range of eucalypt species (evergreens) indicated that the trees use much more water than the alternative cover of grasslands, in large part as a result of their sustained use of water during winter. On the studied sites in Gauteng and Mpumalanga highveld, established trees have the potential to reduce effective rainfall by as much as 50% of the total rainfall.

While this study relates to all types of hydrological system, the use of trees to reduce the recharge component of the hydrological budget for mined sites is a primary application on this potentially significant innovation.

4.8 Wetlands and riparian corridors

As indicated in the literature review, wetlands and riparian corridors are areas where there is a direct interaction between surface water, groundwater and vegetation. They are also areas of high biodiversity and provide habitat for fauna and flora that are absent from the surrounding areas.

Vegetation of riparian corridors is often very different from that of the surrounding areas and the typical species may have affinities with different biomes. In general, the riparian vegetation of the coastal belt, the lowveld and the arid interior comprises thicket and savanna species. An exception to this generalisation is the fynbos or afromontane forest vegetation found on many of the coastal river systems in the western and southern Cape. In the high rainfall grasslands, seasonally high groundwater levels causes the development of wetlands, in topographic low points, along stream lines, and on localised depressions and zero order channels.

4.8.1 *Wetlands*

Cowan (1995a) provides a synthesis of information on South African wetlands. Wetlands in South Africa can be divided into broad regional groups but a more useful categorisation is the functional one (after Cowan 1995b):

- Salt water - including:
  - estuarine and lagoonal - with connections to the marine environment; and
  - saline (internal drainage) - salt marshes and the pans of the interior plateau including the karoo and the highveld.
- Fresh water - including:
  - Riverine wetlands

- → perennial, including inland deltas
  - → seasonal including floodplains
- Lacustrine (lakes)
  - → permanent lakes and pans
  - → seasonal, including floodplain lakes (>8ha)
- Palustrine (marshes, swamps, peatlands, swamp forests, springs and oases; with emergent (fringe) vegetation)
  - → permanent
  - → seasonal.

The synthesis did not examine the importance of groundwater to these different systems but where these systems are perennial and the rainfall is (strongly) seasonal, (shallow) groundwater is assumed to make an important contribution. Most of the interior wetlands are thought to be maintained primarily by surface water flow with a limited component groundwater discharge from local sources. Groundwater is likely to contribute more to permanent lakes, pans and palustrine features. Groundwater-vegetation interactions are likely to be more important in the deep Cainozoic sands of the coastal belt where phreatophytes may also abstract groundwater without there being any groundwater discharge. These are really crude generalisations and a more detailed analysis is urgently needed.

4.8.2 *Riparian corridors*

There has recently been a comprehensive synthesis of information on the ecology of South African river systems (Davies *et al.* 1993). It is evident from this synthesis that very little is known about the relative importance of surface and groundwater to these riparian systems. Most of the concern about river systems has been about the impacts of dams and water diversion schemes on the surface water related ecology (e.g. flow reductions, flooding regimes) of the rivers, although this undoubtedly influences groundwater also. We were not able to locate studies which examined the groundwater dynamics (e.g. groundwater influence or effluence) caused by alterations in surface water dynamics in these river systems. The available information on actual and potential impacts of groundwater abstraction on river systems (e.g on river bed aquifers and bank storage) has been reviewed above. Understanding of the groundwater component of these systems is poor. Special attention needs to be given to the hyporhoeic (permanently wet and biologically active) component of the many non-perennial river systems (Davies *et al.* 1993).

South Africa does have a number of relatively extensive riparian wetland systems which can be classified as follows (after Rogers 1995):

➢ Riparian fringes: these occur along water courses, typically in hydromorphic soils and the structure and species composition are strongly influenced by flooding patterns. The vegetation varies from grasses and sedges (typical of highveld rivers) to shrubs, woodland and forest. The most marked contrasts with the surrounding areas are in semi-arid and arid regions. River Systems in these areas may lose large quantities of water to groundwater recharge, e.g. Limpopo, Molopo and Kuruman, or replenish bank storage for use by riparian vegetation, e.g. Sabie and Orange Rivers.

- Riparian swamp forest: these forests are permanently inundated. They are found mainly along freshwater streams and rivers on the Kwa-Zulu/Natal coastal belt.

- Karoo salt flats: these are connected to the drainage systems and are fed by groundwater discharge episodically during wet periods.

- Floodplain vleis: these comprise a mixture of permanent or seasonal riverine marshes and swamps and periodically inundated grassy floodplains. Examples include the floodplain at Nylsvley.

- Storage floodplains: these are similar to those above but also retain water in oxbow lakes and back swamps for long periods between floods. Examples include the Pongolo, Mfolosi and lower Limpopo River systems.

The ecology and dynamics of these systems are poorly understood but the systems are important habitats for waterbirds and amphibians despite their very limited extent. Botanical surveys have been conducted for a few of the 38 riparian wetlands listed by Rogers (1995) but only two have been studied in any detail: Nylsvley (Tarboton 1987; Coetzee & Rogers 1991; Rogers & Higgins 1993) and the Pongolo floodpain (Heeg and Breen 1982). An overview is given in Breen *et al.* (1988). Studies of the Sabie River system are underway and a few reports have been published recently. In many ways these systems are similar to those found in the Murray-Darling basin in Australia where groundwater plays a key role. Groundwater abstractions will undoubtedly affect these systems and research on these systems should have a high priority.

5. CLASSIFICATION OF VEGETATION - GROUND-WATER INTERACTIONS

5.1 Elements of a classification

Dependency of Vegetation on Groundwater

The degree of dependence of vegetation on groundwater as a source of water and survival can be used to separate types of vegetation.

(i) Obligatory phreatophytes would be most vulnerable to impacts caused by groundwater exploitation, or some other cause of reduced groundwater.

(ii) Facultative phreatophytes exploit the groundwater without necessarily being dependent on it for survival.

(iii) Vegetation that is not associated with groundwater.

Social Importance of the Groundwater resource

How important is groundwater to local communities as a water resource.

1. Dependent on groundwater. Groundwater is the primary or sole water resource.
2. Groundwater is a supplementary water resource.
3. Groundwater is not used as such.

Over about two-thirds of South Africa's land area (the drier interior and west) people are commonly directly dependent on groundwater. Rural communities over much of the rest of the country may also be dependent on groundwater, but indirectly so in that dry season supply comes from groundwater fed springs or baseflow in perennial streams.

Climatic controls (potential to recharge groundwater)

The expected difference between rainfall and evaporation can be seen as potential groundwater recharge. Key characteristics of climatically controlled recharge are amount of recharge and dependability (variability) of recharge.

(i) Mean annual precipitation exceeds annual evaporation on a regular basis. Such situations are rare in South Africa, but would indicate a high, dependable groundwater recharge.

(ii) Rainfall is strongly seasonal; multi-day periods occur seasonally when rainfall exceeds evaporation, resulting in deep percolation of water beyond the reach of plant roots and hence recharge of groundwater.

(iii) Rainfall is low and highly variable, with rare high rainfall events leading to groundwater recharge. This is typical of most of the arid and semi-arid parts of South Africa. Recharge is therefore likely to occur episodically (once in a number of years), and is not dependable in the short term.

Water use characteristics of Vegetation (vegetal modification of recharge potential)
The characteristic water use of different vegetation types is a function of the following factors:

1. Stomatal conductance (or its inverse, the resistance to water flow through the leaves) and stomatal behaviour.
2. Leaf area index (area of leaves relative to ground surface area).
3. Seasonality of leaves: evergreen, cold deciduous or facultative deciduous.
4. Rooting depth and effectiveness of roots at various depths.

Landscape controls on water use by vegetation
Plants need access to water within their rooting zone and at water potentials of 0 to -1.5 Mpa. This may be termed "profile available water". If the profile is effectively shallow, or has a low water capacity for another reason then profile available water will limit the impact of vegetation on recharge or groundwater. The availability of water to plants in the soil profile is a function of

(i) plant rooting characteristics (the ability and tendency to root deeply or otherwise),
(ii) the penetrability of the soil to roots,
(iii) the water holding capacity of the soil (texture and porosity).

Groundwater characteristics
Depth to groundwater (accessibility to plants)
Porosity and permeability of aquifers
Storage capacity of the aquifers
Controls exerted by lithology (frequency and location of sources of groundwater)

5.2 A groundwater viewpoint

The table below describes a possible classification of vegetation groundwater interactions from a groundwater resource perspective, in which the importance of the potential role of vegetation in affecting recharge is ranked. The rationale behind this classification is that where the groundwater resource is large, and where the soil profile available water is high, the role of vegetation will assume greater importance. The size of the role of vegetation (size of recharge reduction caused by a vegetation type) is not incorporated.

Recharge Potential		**High Profile Available Water Capacity**		**Low Profile Available Water Capacity**	
Potential Recharge is High		*Large aquifer capacity*	*Small aquifer capacity*	*Large aquifer capacity*	*Small aquifer capacity*
	Dependable (low variability)	1*	2	2	3
	Erratic (high variability)	2	3	3	4
Potential Recharge is Low	*Dependable*	1	2	2	3
	Erratic	2	3	3	4

* **Vegetation Importance Ranking:** 1. = Role of vegetation is very important, 4. = Role of vegetation is insignificant.

6. RESEARCH ISSUES AND PRIORITIES

The purpose of this chapter is to identify a framework for focussing research in the area of vegetation-groundwater interactions in South Africa over the next five years. The approach is based on the needs expressed at the Nylsvley workshop of September 1996 (see appendix 1). These are organised within the conceptual framework produced by the review of existing information during this project.

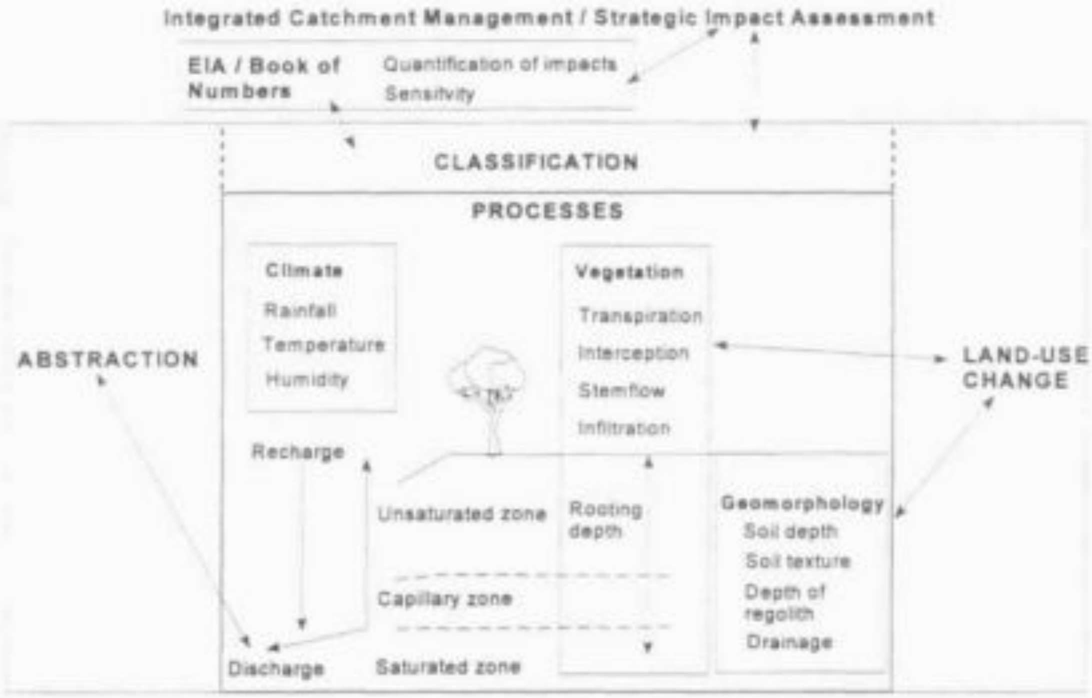

Figure 6.1: A conceptual framework for the research issues in the area of groundwater-vegetation interactions.

6.1 The need for research

The literature review and collation of information on vegetation - groundwater interactions in southern Africa show that while there is a reasonable understanding of these interactions in the scientific community at large, there are few examples of detailed studies in South Africa. Applied research in this area is therefore necessary to improve land-use and groundwater management and conservation.

Table 6.1 shows a rough rating of the state of our knowledge on vegetation and groundwater interactions relative to the expected importance of the groundwater resource (by aquifer type) and the significance of vegetation-groundwater interactions. This table can guide research prioritization on a broad regional scale, but may overlook important localised situations. From our current assessment it appears that the dolomite/limestone and Kalahari sands aquifer types are relatively unimportant, while coastal sands, some alluvial aquifers and the secondary, hard-rock aquifers are important. It appears that the extent and behaviour of the groundwater in the hard rock situations relative to spring discharges and base flows in streams is inadequately understood. The importance of springs and low flows, and low yielding aquifers that are exploited directly may be most critical from the point of view of rural communities.

Table 6.1: Summary of information on vegetation-groundwater interactions in Southern Africa and indication of priority research needs.

	Primary Aquifers			Secondary aquifers	
	Recent coastal sands	Alluvial	'Kalahari Sand' deposits	Dolomite and Limestone	Cracks, fissure etc. in hard rock
Importance to households	High locally, e.g. Zululand	Locally important	Low	Low	High
Importance for ecological reserve	Relatively high	Relatively high: localised	Low	Low	Usually low: but high for riparian habitats & upland wetlands
Information on Vegt-G/w interactions	Some knowledge: tendencies clear	Some situations are well understood	Anecdotal information only; poorly quantified	Unknown	Anecdotal information: Indirect from empirical studies
Strength of the Vegt-G/w interaction	Large	Large	Low to moderate (depending on climate)	Nothing known	Locally very high, e.g. afforestation; but usually low, e.g. Karoo

6.1.1 *Support for broad-scale policy and planning relating to groundwater resources*

There is a need, at the national policy-making and at the regional and local planning level, for tools to support decision-making aimed at managing the hydrological cycle as a whole. Policy makers, integrated catchment managers and planners should incorporate an understanding of the potential impacts on both groundwater and vegetation. This should be both from the perspective of protecting the ecological reserve, where groundwater resources are used by man, and managing land-cover to manipulate recharge to sustain groundwater resources for use elsewhere.

Literature reviewed as part of this project showed that the vegetation cover is one of the factors which control the rate of recharge. Other factors, such as climate, topography and geology, are equally important co-determinants, but vegetation cover differs in that it is subject to change and manipulation over policy-relevant time-scales of a few years or decades. It follows that decisions about land use have impacts on land cover, and land cover has impacts on the groundwater recharge rate. This in turn controls the permissible groundwater abstraction rate, as well as baseflow to streams, rivers and wetlands.

6.1.2 *Increasing general awareness*

Anyone who manages groundwater resources or land-cover, including farmers, foresters and developers, has the potential to impact vegetation and groundwater in vulnerable areas. It is therefore important that the results of scientific research are accessible to this wider audience. Non-technical literature summarising salient issues and increasing impact awareness should be produced once the research has been carried out.

6.2 Research fields

6.2.1 *Identification of Groundwater Dependent Ecosystems*

In order to determine what portion of groundwater should be set aside for the "ecological reserve", there is a need for understanding of vegetation communities or ecosystems that are dependent on groundwater for their normal functioning. There is a need to identify and map these groups, and to develop an understanding of the vulnerability or resilience to changes in the groundwater system that sustains them. How extensive are they on a national basis? How vulnerable are they to changes in groundwater level? An ability to predict the rate and expense of impacts is needed as it is likely that trade-off decisions will have to be taken.

As regards to the identification of vegetation that is dependent on groundwater, the recommended approach to this issue would be to use remote sensing. Vegetation which is using groundwater (with a consequent high assurance of supply) can be expected to have green leaf and a low leaf temperature in seasons well outside the rainy period. Both of these are characteristics are detectable from satellite-based sensors such as the AVHHR instrument, which provides a 1 km x 1 km resolution, and the MODIS instrument (due for launch in 1998) with a 250 m x 250 m resolution. By combining thermal band anomaly detection plus real-time climate data, areas of a seasonally cool and green vegetation could be pinpointed with sufficient resolution for regional and local needs. Some information on water use could probably also be inferred, but the main use would be to direct the location of modelling and ground validation studies to where they are needed.

6.2.2 *Assess the effects of groundwater abstraction on vegetation.*

The key issues with respect to vegetation dependent on groundwater for its survival are thought to be:

For deep rooting plants above shallow groundwater:

- what is the maximum depth at which they can extract water?
- what is the maximum rate of drawdown of the water table that they are able to track?

- will plant recruitment continue under a situation of groundwater depletion?

For groundwater fed wetlands:

- what contraction of the wetland community can be expected for a certain drawdown of the head in the aquifer
- what extent of wetland community loss is tolerable such that the ecosystem remains sustainable.

In reality it is likely that some form of trade-off between development and conservation may be needed, and this points to the need for a predictive capability as regards an ecosystem response to changes in groundwater regime.

These issues will govern permissible levels of changes to the water table, and therefore determine, for instance, the spacing of boreholes of well fields, pumping regimes and drawdown rates. They will need to be determined using experimental techniques in the field, with creative application of natural abundance isotope studies and manipulative trials. The task is achievable because the total number of phreatophytic species and communities is thought to be relatively small. However, the priorities here ought be the "hot-spots" determined by the studies described in Section 6.2.1.

The workshop identified the following key research topics for attention (A = highest priority; C = lowest priority) : -

A. Effects on alluvial aquifers with phreatophyte communities, for example the Limpopo, and other rivers with extensive alluvial beds.
A. Effects on coastal aquifers feeding lagoons, coastal marshes, and similar systems; a specific case is the groundwater-based irrigation on the Cape West Coast.
A. Effects on springs and base flows in Eastern seaboard regions (high and moderate rainfall regions), where groundwater frequently discharges at springs, or people are dependent on perennial streams.
A: Effects on dolomite system aquifers which discharge along the Mpumalanga and Northern Province escarpment (Wolkberg, and "Sabie" catchment).

B. Exploited dolomite aquifers elsewhere.
B. Mine de-watering and its effects on groundwater tables, wetlands (drying-up) and water quality issues.

C. Heavy exploitation of groundwater for irrigation (for example in the Tosca, Dendron and Coetsersdam areas in the North West Province) - what are the effects on vegetation?
C. Are phreatophytes in bedrock river systems (remote rivers) sensitive to groundwater manipulation?
C. Does groundwater exploitation in the karoo increase the risk of donga formation and erosion of the limited alluvial bank storage?
C. Are baobabs being affected by groundwater exploitation?

6.2.3 *Assess the effects of changing vegetation cover and condition on groundwater.*

In order to manage water as a single common resource to achieve optimum, long term, environmentally sustainable social and economic benefit, and to allocate a reserve for human use and ecological integrity, it is necessary to have a quantitative understanding of how changes in vegetation cover and condition affect the hydrological cycle, and specifically groundwater resources. It is therefore necessary to identify, characterise and quantify the important interactions of this kind in South Africa. The preliminary identification of these situations should come from the broad scale studies proposed in Sections 6.2.1 & 6.2.2. Specific attention would then need to be given to understanding the process of these interactions and quantifying the effects of land cover change and land degradation on groundwater resources, and groundwater fed low flows and springs.

Research will be carried out in some areas of the country on this issue in connection with the Working for Water Programme, therefore collaboration between the WRC and the Working for Water Programme is recommended.

The workshop identified the following key topics for attention:

A. Afforestation effects on groundwater
A. The effects of land degradation related to rural settlements - emphasizing the effect degradation has on local groundwater recharge and thus on local water supply.

B. Management of veld, and its effects on groundwater. A key form of veld management is bush clearing in savanna, or thicket, to plant crops or augment groundwater recharge; the effects of bush clearing on water quality should also be addressed.
B. The effects of the clearing of alien plants on groundwater and catchment hydrology.
B. Selection of species for woodlot planting that will minimise the impacts on groundwater and are environmentally acceptable.

C. Effects of sugar cultivation on groundwater.
C. Effects of maize cultivation on groundwater.

6.2.4 *Quantitative modelling of groundwater-vegetation interactions.*

Guidelines are needed for the assessment and quantification of recharge under different types of vegetation cover, for given combinations of climate, topography and substrate. For convenience, these guidelines may take the form of a 'book of numbers', or nomograms or similar device, but underlying them will need to be some form of model. The characteristics of this model are as follows:-

➢ It ought be from the general class of biophysical models known as SVAT models (Soil-vegetation-atmosphere transfer models). These have reached a high level of development, largely due to the interest of the climate modelling community.

➢ It will ultimately need to be two-dimensional, to cope with the fact that areas of strong vegetation-groundwater interaction are localised within the landscape, but are dependent on their context within the landscape (for instance, on hillslope hydrology, or on advection due to the oasis effect).

➢ It will need to have a root extraction function which is significantly more elaborate than most current SVAT models, which tend to treat the soil as a one-or-two compartment bucket of rather shallow depth, and with a homogeneous distribution of roots.

➢ It must link into, or incorporate, appropriate groundwater models or components.

The latter two points pose key research needs. A viable strategy would be to obtain one or more existing one-dimensional SVAT models, and use them as a foundation for further development. They could be initially applied as a sensitivity analysis, using existing estimates of vegetation and soil parameters, to determine which parts of the country and which land cover transformations would warrant more intensive research. The next step would be to improve their parameterisation and validation with locally collected information, using ecophysiological (porometry) and micrometeorological techniques (Bowen ratio and eddy correlation). The third step would be to improve their treatment of deep rooting, by increasing the number of rooting layers and by introducing defensible root extraction functions. The final step would be to convert them to a two-dimensional form.

The policy guidelines could emerge iteratively from this process. Even application of the existing models, with available data, would help to constrain the policy choices. Further elaboration, refinement and testing of the model would lead to successive improvements.

6.2.5 *Mapping of biohydrogeological response units and identification of "hot-spots".*

There are research needs at two scales. The first is at the regional and national scales, to delimit those areas where policy should be focussed. The products would be maps, probably at a scale of 1:500 000 or 1:1 M, which integrate broad climatic regions, groundwater resources and vegetation covers to show where potential land cover changes may have a significant impact on water resources, and where groundwater use may have an impact on vegetation cover.

The nature of the groundwater-vegetation interactions in southern Africa is that it is generally highly localised within the landscape - for instance, in pockets of deeper soils and along riparian aquifers. These will not be visible on the broad-scale maps generated above. There is a need, once the broad regions have been identified, to show where 'hot-spots' of important interaction occur.

There are two possible approaches to this issue. The first is a Geographic Information System overlay approach, in which the known groundwater resources, aquifer characteristics and local importance of the groundwater resource are overlaid with climatic and vegetation information to produce a risk map. This map will be qualitative, but could be a useful a first approach to the broad-scale issue. It does not have the resolution, nor mechanistic insight, to address the finer-scale issues.

The second approach is to apply a SVAT model on a spatially-explicit basis. This would supply both the causality and resolution, but would impose data demands which are unattainable at the national scale in the near future. Until the models are adapted and tested, it would also involve many unacceptable assumptions.

6.3 Other Issues

6.3.1 *Evaluation of the present groundwater monitoring programme*

The present groundwater monitoring programmes and recommended methodology, co-ordinated by the Department of Water Affairs and Forestry, does not address the groundwater-vegetation interactions. Although the information on this topic is limited, the present approach needs to be evaluated and adapted to incorporate our current understanding of the principles and the relative importance of the processes involved.

6.3.2 *Capacity Building*

There are few hydrogeologists, botanists or ecologists in South Africa who have carried out research on groundwater-vegetation interactions. Capacity building therefore should also focus on building inter-disciplinary skills to facilitate the trans-disciplinary work that is needed to support the sustainable utilisation of groundwater resources.

6.4 Summary of research requirements

The research topics are summarized in approximate order of priority.

- Identify and map groundwater dependent human communities and ecosystems (so-called hot spots).
- Development of a classification scheme to guide/assist evaluation of the importance of groundwater-vegetation interactions and impact vulnerability.
- Scientific field investigations aimed at improving the understanding and quantification of the processes involved (isotope studies, monitoring the affects of changing groundwater/vegetation conditions, alien vegetation removal, etc).
- Development of guidelines and/or expert systems to support policy makers and planners assess the importance of groundwater-vegetation interactions and impact vulnerability.

- GIS maps (regional and local scales) of biohydrogeological response units and hot-spots.

- Quantitative modelling of interactions: d., 2D and spatially explicit soil-vegetation-atmosphere transfers.

- Publication of a non-technical booklet to increase public awareness of the importance of groundwater- vegetation interactions and potential vulnerability.

Figure 6.1: Outline of research requirements and deliverables.

Remote sensing	Field research	Numerical modelling	Literature review
⇓	⇓	⇓	⇓

Quantified understanding of typical South African vegetation-groundwater interactions.

⇓	⇓	⇓	⇓
Classification scheme	GIS maps	Guidelines/ Expert systems	Non-technical booklet

7. BIBLIOGRAPHY

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.

Adams, ME 1967. A study of the ecology of *Acacia mellifera, A. seyal* and *Balanites aegyptaica* in relation to land clearing. *Journal of Applied Ecology* 4: 221-237.

Allison, GB, Stone, WJ & Hughes, MW 1985. Recharge in karst and dune elements of a semi-arid landscape as indicated by natural isotopes and chloride. *Journal of Hydrology* 76: 1-25.

Archer, S 1989. Have southern Texas savannas been converted to woodlands in recent history. *American Naturalist* 134: 545-561.

Awe, JO, Shepherd, KR & Florence, RG 1976. Root development in provenances of *Eucalyptus camaldulensis* Dehn. *Australian Forestry* 39: 201-209.

Bacon, PE, Stone, C, Binns, DL, Leslie, DJ & Edwards, DW 1993. Relationship between water availability and *Eucalyptus camaldulensis* growth in a riparian forest. *Journal of Hydrology* 150: 541-561.

Bari, MA & Schofield, NJ 1992. Lowering of a shallow, saline water table by extensive eucalypt reforestation. *Journal of Hydrology* 133: 273-291.

Barnes, DL & Franklin, MJ, 1970. Runoff and soil loss on a sandveld in Rhodesia. Proc. *Grassland Society of Southern Africa.* 11: 135-138.

Barnes, RD, Filer, DL & Milton, SJ 1996. *Acacia karoo.* Monograph and annotated bibliography. Tropical Forestry Papers No. 32. Oxford Forestry Institute, Oxford.

Barnett, SR 1989. The effect of land clearance in the Mallee region on River Murray salinity and land salinisation. *Journal of Australian Geology & Geophysics* 11: 205-208.

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

Bayer, AW 1943. The thornveld tree: a note on plant adaptation. *South African Journal of Science* 34: 44-55.

Bekker, P, 1992. The geohydrological investigation for supplementary groundwater reserves in the Kuiseb Delta - Walvis Bay State Water Scheme. Unpublished departmental report, GH 3779, Department of Water Affairs, Private Bag X 313, Pretoria.

Bell, RW, Schofield, NJ, Loh, IC & Bari, MA 1990. Groundwater response to reforestation in the Darling Range of Western Australia. *Journal of Hydrology* 115: 297-317.

Belsky, AJ, Amundson, RG, Duxbury, JM, Riha, SJ, Ali, AR & Mwonga, SM 1989. The effects of trees on their physical, chemical, and biological environments in semi-arid savanna in Kenya. *Journal of Applied Ecology* 26: 1005-1024.

Belsky, AJ, Mwonga SM, Amundson, RG, Duxbury, JM & Ali, AR 1993a. Comparative effects of isolated trees on their under-canopy environments in high- and low-rainfall environments. *Journal of Applied Ecology* 30: 145-155.

Belsky, AJ, Mwonga, SM & Duxbury, JM 1993b. Effects of widely spaced trees and livestock grazing on understorey environments in tropical savannas. *Agroforestry Systems* 24: 1-20.

Bernaldez, FG, Perez, CP & Carmona, AS 1985. Areas of evaporative discharge from aquifers: little known Spanish ecosystems deserving protection. *Journal of Environmental Management* 21: 321-330.

Bernaldez, FG, Rey Benayas, JM & Martinez, A. 1993. Ecological impact of groundwater extraction on wetlands (Douro Basin, Spain). *Journal of Hydrology* 141: 219-238.

Berndtsson, R & Larson, M 1987. Spatial variability of infiltration in a semi-arid environment. *Journal of Hydrology* 90: 117-133.

Bille, JC 1977. Etude de la production primaire nette d'un ecosysteme sahelien. Trav Doc ORSTOM 65: 82, ORSTOM, Paris.

Blackburn, W 1975. Factors influencing infiltration and sediment production of semi-arid rangelands in Nevada. *Water Resources Research* 11: 929-937.

Blight, GE, 1987. Lowering of groundwater table by deep-rooted vegetation - The geotechnical effects of water table recovery. In Hanrahan, ET, Orr, TLL and Widdis, TF, (Editors), *Groundwater effects in geotechnical engineering*. Balkema, Rotterdam. pp. 285 - 288.

Bobba, AG, Bukata, RP & Jerome, JH 1992. Digitally processed satellite data as a tool in detecting potential groundwater flow systems. *Journal of Hydrology* 131: 25-62.

Bosch, JM, 1980. 'n Ontleding van die Cathedral Peak hidrologiese eksperimente. Unpublished M.Sc. thesis, Faculty of Forestry, University of Stellenbosch.

Bosch, JM & Hewlett, JD 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. *Journal of Hydrology* 55: 2-23.

Borg, H, Stoneman, GL & Ward, CG 1988. The effect of logging and regeneration on groundwater, streamflow and stream salinity in the southern forest of Western Australia. *Journal of Hydrology* 99: 253-270.

Braune, E, 1991. Hydrology of the lower Kuiseb River. In: Slabbert, A. (compiler), Proc. Symp. "Water resource development for Walvis Bay", Walvis Bay, February, 1991. Department of Water Affairs, Pretoria.

Braune, E and Dziembowski, ZM, 1997. Towards integrated groundwater and surface water management in South Africa. Proc. Eighth South African National Hydrology Symposium, Pretoria, 17 -19 November, 1997.

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

Breen, CM, Rodgers KH & Ashton, PJ 1988. Vegetation processes in swamps and flooded plains. In: *Vegetation of inland waters* (ed. JJ Symoens). Kluwer Academic Publishers, Netherlands.

Breman H & Kessler JJ 1995. *Woody plants in agro-ecosystems of semi-arid regions*. Advanced series in agricultural sciences No. 23, Springer-Verlag, Berlin.

Bren, LJ & Gibbs, NL 1986. Relationships between flood frequency, vegetation and topography in a river red gum forest. *Australian Forest Research* 16: 357-70.

Bruinzeel, LA 1989. Nutrient cycling in moist tropical forests: the hydrological framework. In: *Mineral nutrients in tropical forest and savanna ecosystems* (ed. J Proctor), pp 383-415. Special Publication No. 9, British Ecological Society, Blackwell, Oxford.

Brunel, J-P, Walker, GR & Kennett-Smith, AK 1995. Field validation of isotopic procedures for determining sources of water used by plants in a semi-arid environment. *Journal of Hydrology* 167: 351-368.

Burch, GJ, Bath, RK, Moore, ID and O'Loughlin, EM 1987. Comparative hydrological behaviour of forested and cleared catchments in southeastern Australia. *Journal of Hydrology* 90: 19-42.

Busch, DE, Ingraham, NL and Smith, SD 1992. Water uptake in riparian phreatophytes of the south-western United States: a stable isotope study. *Ecological Applications* 2: 450-459.

Calder IR 1992. Water use of eucalypts - a review. In: *Growth and water use of forest plantations* (eds IR Calder, RL Hall, PG Adlard), pp 167-179. Wiley, London.

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.

Cannon, WA 1949. A tentative classification of root systems. *Ecology* 30: 544-548.

Caplan, M 1995. Collapsing Baobabs. *Veld & Flora* 81(1): 22-23.

Carbon, BA, Bartle, GA, Murray, AM and Macpherson, DK 1980. The distribution of root length, and the limits to flow of soil water to roots in a dry sclerophyll forest. *Forest Science* 26: 656-664.

Carbon, BA, Roberts, FJ, Farrington, P & Beresford, JD 1982. Deep drainage and water use of forests and pastures grown on deep sands in a mediterranean environment. *Journal of Hydrology* 55: 53-64.

Carlson, DH, Thurow, TL, Knight, RW & Heitschmidt, RK 1990. Effect of honey mesquite on the water balance of Texas Rolling Plains rangeland. *Journal of Range Management* 43: 491-496.

Chesterfield, EA 1986. Changes in the vegetation of the river red gum forest at Barmah, Victoria. *Australian Forestry* 49: 4-15.

Coetzee, MAS & Rogers, KH 1991. Environmental correlates of plant species distribution on the Nyl River floodplain. *South African Journal of Aquatic Sciences* 17: 44-55.

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

Colvin, CC, Conrad, J, Cave, L, Sililo, OTN, Weaver, JMC & Reinhardt, CF, 1997. *Assessment of the impact of agricultural practices on the quality of groundwater resources in South Africa*. Draft Water Research Commission Report. WRC, Pretoria.

Cornish, PM 1993. The effects of logging and forest regeneration on water yields in moist eucalypt forest in New South Wales, Australia. *Journal of Hydrology* 150: 301-322.

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

Cowan, GI 1995b. Wetland regions of South Africa. In: Wetlands of South Africa (ed. GI Cowan), pp 21-31. Department of Environment Affairs and Tourism, Pretoria.

Croft, AR 1950. A water cost of runoff control. *Journal of Soil and Water Conservation* 5: 13-15.

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.

CTFT 1988. *Faidherbia albida* (Del.) A. Chev. monographie. Cent Tech For Trop, Nogent-sur-Marne, France.

Culf, AD, Allen, SJ, Gash, JHC, Lloyd, CR & Wallace, JS 1993. Energy and water budgets of an area of patterned woodland in the Sahel. *Agricultural and Forest Meteorology* 66: 65-80.

Dancette, C & Poulain, JF 1969. Influence of *Faidherbia albida* on pedoclimatic factors and crop yields. *African Soils* 14: 143-184.

Dao, TH 1993. Tillage and winter wheat residue management effects on water infiltration and storage. *Soil Science Society of America Journal* 57: 1586-1594

Davies, BR, O'Keeffe, 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, GB & Peck, AJ 1986. Estimating evapotranspiration by analysis of bore hydrographs. In: Symposium on conjunctive water use, Budapest, July 1986 (ed. SM Gorelick, pp 313-321. IAHS Publication No 156, IAHS, Washington.

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.

Dawson, TE 1993a. Water sources of plants as determined from xylem-water isotopic composition, distribution, and water relations. In: Stable isotopes and plant carbon-water relations (ed. JR Ehleringer, AE Hall & GD Farquhar), pp 465-495. Academic Press Inc., San Diego.

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

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

Dawson, TE and Ehleringer, JR 1991. Streamside trees that do not use stream water. *Nature* 350: 335-337.

Dawson, TE & Pate, JS 1996. Seasonal water uptake and movement in root systems of Australian phreatophytic plants of dimorphic morphology: a stable isotope investigation. *Oecologia* 107: 13-20.

De Beer, GCO, 1996. Short report on the monitoring of Limpopo Riparian vegetation: Greefswald 37MS: Period July 1996. The Northern Province Department of Environmental Conservation and Tourism, Pietersburg.

De Beers Consolidated Mines (undated). The Venetia balance: diamonds, water and environmental responsibility. {Environmental information brochure produced by Corporate Communications Department of Anglo American Corporation, Johannesburg. 20 pp.}.

De Jong, E & Kachanowski, RG undated. The role of grasslands in hydrology.

Dell, B, Bartle, JR & Tracey, WH 1983. Root occupation and root channels of Jarrah forest subsoils. *Australian Journal of Botany* 31: 615-627.

De Villiers, G. Du T. 1975. Reënvalonderskeppingsverliese in die Republiek van Suid Afrika - 'n streekstudie. Ph.D. Thesis, Department of geography, University of the Orange Free State, Bloemfontein. pp. 219.

De Villiers, G. Du T. 1982. Predictive models for estimating net rainfall and interception losses in savanna vegetation. *Water SA* 8: 208-212.

De Villiers, G. Du T. & De Jager, M 1981. Net rainfall and interception losses in *Burkea africana Ochna pulchra* tree savanna. *Water SA* 7: 249-254.

Devito, KJ, Hill, AR and Roulet, N 1996. Groundwater-surface water interactions in headwater forested wetlands of the Canadian shield. *Journal of Hydrology* 181: 127-147.

Dexter, BD, Rose, HJ & Davies, N 1986. River regulation and associated forest management problems in the River Murray red gum forests. *Australian Forestry* 49: 16-27.

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.

Doley, D 1967. Water relations of *Eucalyptus marginata* SM. under natural conditions. *Journal of Ecology* 55: 597-614.

Donovan, LA & Ehleringer, JR 1994. Water stress and use of summer precipitation in a Great Basin shrub community. *Functional Ecology* 1994, 8: 289-297 (abstract).

Dumsday, RG, Pegler, R & Oram, DA 1989. Is broadscale revegetation economic and practical as a groundwater salinity management tool in the Marray-Darling basin? *Journal of Australian Geology & Geophysics* 11: 209-218.

DWAF, 1986. Management of the Water Resources of South Africa. Department of Water Affairs (and Forestry), Pretoria.

DWAF, 1997. White paper on a national water policy for South Africa. Department of Water Affairs and Forestry, Pretoria. April, 1997.

Dye, PJ 1996. Climate, forest and streamflow relationships in South African afforested catchments. *Commonwealth Forestry Review* 75: 31-38.

Dye, P.J. and Poulter, A.G., 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 & Spear, PT 1982. The effect of bush clearing and rainfall variability on grass yield and composition in south-west Zimbabwe. *Zimbabwe Journal of Agricultural Research* 20: 103-117.

Eastham, J, Rose, CW, Cameron, DM, Rance, SJ and Talsma, T 1988. The effect of tree spacing on evaporation from an agroforestry experiment. *Agricultural and Forest Meteorology* 42: 355-368.

Eastham, J, Rose, CW, Cameron, DM, Rance, SJ, Talsma, T & Charles-Edwards, DA 1990a. Tree/pasture interactions at a range of tree densities in an agroforestry experiment. II Water uptake in relation to rooting patterns. *Australian Journal of Agricultural Research* 41: 697-707.

Eastham, J, Rose, CW, Cameron, DM, Rance, SJ, Talsma, T & Charles-Edwards, DA 1990b. Tree/pasture interactions at a range of tree densities in an agroforestry experiment. III Water uptake in relation to soil hydraulic conductivity and rooting patterns. *Australian Journal of Agricultural Research* 41: 709-718.

Ehleringer, JR, Phillips, SH, Schuster, WSW & Sandquist, DR 1991. Differential utilisation of summer rains by desert plants. *Oecologia* 88: 430-434.

Elkins, NZ, Sabol, GV, Ward, TJ & Whitford, WG 1986. The influence of subterranean termites of hydrological characteristics of a Chihuahuan desert ecosystem. *Oecologia* 68: 521-528.

Farrington, P, Greenwood, EAN, Bartle, GA, Beresford, JD & Watson, GD 1989. Evaporation from a *Banksia* woodland on a groundwater mound. *Journal of Hydrology* 105: 173-186.

Farrington, P, Watson, GD, Bartle, GA & Greenwood, EAN 1990. Evaporation from dampland vegetation on a groundwater mound. *Journal of Hydrology* 115: 65-75.

Farrington P & Bartle GA 1991. Recharge beneath a Banksia woodland and a *Pinus pinaster* plantation on coastal deep sands in south Western Australia. *Forest Ecology & Management* 40: 101-118.

Faulkner, RD & Lambert, RD 1991. The effect of irrigation on dambo hydrology: a case study. *Journal of Hydrology* 123: 147-161.

Feddes, RAS 1977. Compensating measures for groundwater withdrawal. *H2O (Rotterdam)* 10: 86-94. (in Dutch).

Fenner, M 1980. Some measurements on the water relations on Baobab trees. *Biotropica* 12: 205-209.

Ferrar AA (ed.) 1989. Ecological flow requirements for South African rivers. South African National Scientific Programmes Report No. 162, FRD, Pretoria.

Ferrar AA, O'Keeffe JH & Davies BR 1988. The river research programme. South African National Scientific Programmes Report No. 146, FRD, Pretoria.

Flanagan, LB, Ehleringer, JR & Dawson, TE 1992a. Water sources of plants growing woodland, desert and riparian communities: evidence from stable isotopes. In: Ecology and Management of Riparian Shrub Communities, pp 43-47. General Report INT-289, Forest Service, USDA.

Flanagan, LB, Ehleringer, JR & Marshall, JD 1992b. Differential uptake of summer precipitation among co-occurring trees and shrubs in a pinyon-juniper woodland. *Plant, cell and Environment* 15: 831-836.

Franz, EH & Bazzaz, FA 1977. Simulation of vegetation response to modified hydrologic regimes: a probabilistic model based on niche differentiation in a floodplain forest. *Ecology* 58: 176-183.

Furness HD & Breen CM 1980. The vegetation of seasonally flooded areas of the Pongolo river floodplain. *Bothalia* 13: 217-231.

Gee, GW, Wierenga, PJ, Andraski, BJ, Young, MH, Fayer, MJ & Rockhold, ML 1994. Variations in water balance and recharge potential at three western desert sites. *Soil Science Society of America Journal* 58: 63-72.

Gieske, A, Selaolo, E & McMullan, S 1990. Groundwater recharge through the unsaturated zone of southeastern Botswana: a study of chlorides and environmental isotopes. IAHS Publication. No. 191, pp 33-44 (abstract).

Greenwood, E.A.N., Klein, J.D., Beresford, J.D. & Watson, G.D. 1985. Differences in annual evapotranspiration between grazed pasture and *Eucalyptus* species in plantations on a saline farm catchment. *Journal of Hydrology* 78: 261-278.

Greenwood, EAN 1992. Deforestation, revegetation, water balance and climate: an optimistic path through the plausible, impractical and the controversial. In: *Advances in Bioclimatology Volume 1* (ed. G Stanhill) pp 89-154. Springer Verlag, Berlin.

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

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

Heath, J & Heuperman, A 1996. Serial biological concentration of salts - a pilot project. *Australian Journal of Soil and Water Conservation* 9(1): 27-31.

Heeg, J & Breen, CM 1982. Man and the Pongolo floodplain. South African National Scientific Programmes Report No. 56, Foundation for Research and Development, Pretoria.

Heitschmidt, RK & Dowhower, SL 1991. Herbage response following control of honey mesquite within single tree lysimeters. *Journal of Range Management* 44: 144-149.

Hellmers, H, Horton, JS, Juhren, G & O'Keefe, J 1955. Root systems of some chaparral plants in southern California. *Ecology* 36: 667-678.

Heuperman, A 1992. Trees in irrigation areas. The biopumping concept. *Trees and Natural Resources* 34: 20-25.

Heuperman, AF 1995. Salt and water dynamics beneath a tree plantation growing on a shallow watertable. Institute of Sustainable Irrigated Agriculture, Department of Agriculture, Energy and Minerals, Australia.

Helvey, JD & Patric, JH 1965. Canopy and litter interception of rainfall by hardwoods of eastern United States. *Water Resources Research* 1: 193-206.

Hewlett, JD & Bosch, JM 1984. The dependence of storm flows on rainfall intensity and vegetal cover in South Africa. *J. Hydrol.*, 75: 365-381.

Higgins, KB, Lamb, AJ & 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.

Hino, M. Fujita, K & Shutto, H 1987. A laboratory experiment on the role of grass for infiltration and runoff processes. *Journal of Hydrology* 90: 303-325 (abstract).

Hofman, RH and Bush, RA, 1996. Greefswald Schroda Wellfield Monitoring Report no. 22. Anglo American Corporation of South Africa Civil Engineering Department, Johannesburg. Report no. CED/021/96. De Beers Consolidated Mines Ltd, 1996.

Hollis, E & Bedding, J 1994. Can we stop the wetlands from drying up? *New Scientist* No. 1932: 30-35.

Holmes, JW & Colville, JS 1970a. Grassland hydrology in a karstic region in South Australia. *Journal of Hydrology* 10: 38-58.

Holmes, JW & Colville, JS 1970b. Forest hydrology in a karstic region in South Australia. *Journal of Hydrology* 10: 59-74.

Hookey, GR 1987. Prediction of delays in groundwater response to catchment clearing. *Journal of Hydrology* 94: 181-198.

Huff, CR 1992. Riparian vegetation recovery patterns following stream channelisation: a geomorphic perspective. *Ecology* 73: 1209-1226.

Hughes, FMR 1990. The influence of flooding regimes on forest distribution and composition on the Tana River floodplain, Kenya. *Journal of Applied Ecology* 27: 475-491.

Huntoon, PW 1992. Hydrogeologic characteristics and deforestation of the stone forest karst aquifers of South China. *Ground Water* 30: 167-176.

Issar, A, Nativ, R, Karnieli, K & Gat, JR 1984. Isotopic evidence of the origin of groundwater in arid zones. International Atomic Energy Agency, Vienna.

Jackson, IJ 1975. Relationships between rainfall parameters and interception by tropical forest. *Journal of Hydrology* 24: 215-238.

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.

Jayasuriya, MDA, Dunn, G, Benyon, R & O'Shaughnessy, PJ 1993. Some factors affecting water yield from mountain ash (*Eucalyptus regnans*) dominated forest in south-east Australia. *Journal of Hydrology* 150: 345-367.

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

Joffre, R and Rambal, S 1988. Soil water improvement by trees in the rangelands of southern Spain. *Acta Oecologia Oecologia Plantarum* 9: 405-422.

Joffre, R and Rambal, S 1993. How tree cover influences the water balance of Mediterranean shrublands. *Ecology* 74: 570-582.

Johnson, WC, Burgess, RL & Keammerer, WR 1976. Forest overstorey vegetation and environment on the Missouri River floodplain in North Dakota. *Ecological Monographs* 46: 59-84.

Johnston, CD 1983. Estimation of groundwater recharge from the distribution of chloride in deeply weathered profiles from south-west Western Australia. International Conference on Groundwater and Man, Sydney, 5-9 December 1983, pp 143-152. Conference Series No 008, Australian Water Resources Council, Government Publisher, Canberra.

Johnston, CD 1987a. Preferred water flow and localised recharge in a variable regolith. *Journal of Hydrology* 94: 129-142.

Johnston, CD 1987b. Distribution of environmental chloride in relation to subsurface hydrology. *Journal of Hydrology* 94: 67-88.

Johnston, CD, Hurle, DH, Hudson, DR and Height, MI 1983. Water movement through preferred paths in lateritic profiles of the Darling Plateau, Western Australia. Groundwater Research Paper No 1, CSIRO, Melbourne , Australia,

Jolly, ID, Walker, GR & Thorburn, PJ 1993. Salt accumulation in semi-arid floodplain soils with implications for forest health. *Journal of Hydrology* 150: 589-614.

Keeley, JE 1979. Population differentiation along a flood frequency gradient: physiological adaptations to flooding in *Nyssa sylvatica*. *Ecological Monographs* 49: 89-108.

Kelbe, BE, Rawlins, BR and Nomquphu, W, 1995. Geohydrological modelling of St Lucia. Technical Report of Department of Hydrology, University of Zululand, KwaDlengezwa, South Africa.

Kelly, RD & Walker, BH 1976. The effects of different forms of land-use on the ecology of a semi-arid region in south-eastern Rhodesia. *Journal of Ecology* 64: 553-576.

Kemper, NP, 1994. . Greefswald riparian vegetation Monitoring report (1993 annual report) January to December 1993. Chief Directorate of Nature Conservation and Environmental Conservation

Kennard, DG & Walker, BH 1973. Relationships between tree canopy cover and *panicum maximum* in the vicinity of Fort Victoria. *Rhodesian Journal of Agricultural Research* 11: 145-153.

Kerfoot, O 1963. The root systems of tropical forest trees. *Commonwealth Forestry Review* 42: 19-26.

Khan, LR & Mawdsley, JA 1982. Effects of land-use changes on groundwater recharge assessed using a nonlinear catchment model. In: Improvements of methods of long term prediction of variations in groundwater resources and regimes due to human activity, pp 97-106. IAHS Publication No. 136, IAHS, UK.

Kienzle, SW and Schulze, RE, 1992. A simulation model to assess the effect of afforestation on ground-water resources in deep sandy soil. *Water SA* 18: 265-272.

Knoop, WT & Walker, BH 1985. Interactions of woody and herbaceous vegetation in a southern African savanna. *Journal of Ecology* 73: 235-253.

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

Kummerow, J & Mangan, R 1981. Root systems in *Quercus dumosa* Nutt. dominated chaparral in California. *Acta Oecologia Oecologia Plantarum* 2: 177-188.

Kummerow, J 1981. Structure of roots and root systems. In: Mediterranean-type shrublands (eds F Di Castri, DW Goodall & RL Specht), pp 269-288. Elsevier, Amsterdam.

Langkamp, PJ, Farrel, GK & Dalling, MJ 1982. Nutrient cycling in a stand of *Acacia holosericea* A Cunn ex G Don. I. Measurements of precipitation interception, seasonal acetylene reduction, plant growth and nitrogen requirement. *Australian Journal of Botany* 30: 87-106.

Lawson, GW, Jenik, J & Armstrong-Mensah, KO 1968. A study of a vegetation catena in Guinea savanna at Mole Game Reserve (Ghana). *Journal of Ecology* 56: 505-522.

Le Houerou, HN 1992. The role of saltbushes (*Atriplex* spp.) in arid land rehabilitation in the Mediterranean Basin: a review. *Agroforestry Systems* 18: 107-148.

Le Houerou, HN 1994. Drought-tolerant and water-efficient fodder shrubs (DTFS), their role as a "drought insurance" in the agricultural development of arid and smei-arid zones in southern Africa. Report No KV 65/94, Water Research Commission, Pretoria.

Leistner, OA 1967. The plant ecology of the southern Kalahari. Botanical Survey Memoir No.38, National Botanical Institute, Pretoria.

Lewis, DC & Burgy, RH 1964. The relationship between oak tree roots and groundwater in fractured rock as determined by tritium tracing. *Journal of Geophysical Research* 69: 2579-2588.

Lima, WDeP, Zakia, MJB, Libardi, PL & Filho, APDeS 1990. Comparative evapotranspiration of eucalyptus, pine and natural "cerrado" vegetation measure by the soil water balance method. *IPEF International, Piriccaba(1)*: 5-11.

Llamas, MR 1988. Conflicts between wetland conservation and groundwater exploitation: two case histories in Spain. *Environ Geol Water Sci* 11: 241-251.

Llamas, MR 1991. Groundwater exploitation and conservation of aquatic systems. In: Aquifer overexploitation. Proceedings of the 33rd International Congress of the International Association of

Hydrogeologists, Vol 1 General papers, extended abstracts and posters, pp115-131. IAH, Spain.

Low, AB & Rebelo, AG (eds) 1996. *Vegetation of South Africa. Lesotho and Swaziland.* Department of Environment Affairs and Tourism, Pretoria.

Lunt, HA 1934. Distribution of rainfall under isolated forest trees. *Journal of Agricultural Research* 49: 695-703.

LWSK, 1989. Invloed van grondwater onttrekking op karoo-ekologie: Verslag van wetenskaplike taakspan aan LWSK. Technical report, no GH 3630, Department of Water Affairs and Forestry.

Lyford, F & Quashu, H 1969. Infiltration rates as influenced by desert vegetation. *Water Resources Research* 5: 1373-1376.

Mahoney, JM & Rood, SB 1991. A device for studying the influence of declining water table on poplar growth and survival. *Tree Physiology* 8: 305-314 (abstract).

Mahoney, JM and Rood, SB 1992. Response of a hybrid poplar to water table decline in different substrates. *Forest Ecology and Management* 54: 141-156.

Menaut, J-C 1983. The vegetation of African savannas. In: *Tropical savannas.* Ecosystems of the World Vol 13 (ed. Bourliere, F), pp 109-149. Elsevier, Amsterdam.

McFarlane, DJ & George, RJ 1992. Factors affecting dryland salinity on two wheatbelt catchments in Western Australia. *Australian Journal of Soil Research* 30: 85-100.

Meunier, M 1996. Forest cover and floodwater in small mountain watersheds. *Unasylva* 185: 29-37.

Midgley, DC, Pitman, WV and Middleton, BJ 1994. The surface water resources of South Africa 1990. Volumes 1 to 6. Report Numbers 298/1.1/94 to 298/6.1/94 (text) and 298/1.2/94 to 298/6.2/94 (maps), Water Research Commission, Pretoria.

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, 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. *S.A. Forestry Journal* 170: 33-36.

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, and Dean, WRJ, 1996. Karooveld: ecology and management. ARC-Range and Forage Institute, Pretoria.

Moore, A, Opperman, DPJ and van Rooyen, DJ 1982. Redistribution of groundwater in three sub-habitats of a *Burkea* savanna. *Proceedings of the Grasslands Society of Southern Africa* 17: 112-115.

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.

Myers, BJ & Talsma, T 1992. Site water balance and tree water status in irrigated and fertilised stands of *Pinus radiata*. *Forest Ecology & Management* 52: 17-42.

Naeth, MA, Chanasyk, CDS, Rothwell and Bailey, AW 1991. Grazing impacts on soil water in mixed prairie and fescue grassland ecosystems of Alberta. *Canadian Journal of Soil Science* 71: 313-325.

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

Nänni UW (1970) The effect of afforestation on streamflow at Cathedral Peak. *South African Forestry Journal* 74: 6-12.

Nänni, U.W., 1971. The Mokobulaan research catchments. *South African Forestry Journal*, 78: 5-13.

Navar, J & Ryan, R 1990. Interception loss and rainfall redistribution by three semi-arid growing shrubs in northeastern Mexico. *Journal of Hydrology* 115: 51-63.

Nepstad, DC, de Carvalho, CR, Davidson, EA, Jipp, PH, Lefebvre, PA, Negreiros, GH, da Silva, ED, Stone, TA, Trumbore, SE & Veira, S 1994. The role of deep roots in the hydrological and carbon cycles of Amazonian Forests. *Nature* 372: 666-669.

Nilsen, ET, Sharifi, MR, Rundel, PW, Jarrell, WM & Virginia, RA 1983. Diurnal and seasonal water relations of the desert phreatophyte *Prosopis glandulosa* (honey mesquite) in the Sonoran desert of California. *Ecology* 64: 1381-1393.

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

Nkotagu, H 1996. Application of environmental isotopes to groundwater recharge studies in a smei-arid fractured crystalline basement area of Dodoma, Tanzania. *Journal of African Earth Sciences* 22: 443-457.

Nobel, PS 1991. Ecophysiology of roots of desert plants, with special emphasis on agaves and cacti. In: *Plant roots. the hidden half* (eds Y Waisel, A Eshel & U Kafkafi), pp 839-866. Marcel Dekker, New York.

Noble RG & Hemens J 1978. Inland water ecosystems in South Africa - a review of research needs. South African National Scientific Programmes Report No. 34, CSP CSIR (FRD), Pretoria.

Nott, K & Savage, MJ 1985. Root distribution of *Trianthema hereroensis* in the Namib dunes. *Madoqua* 14: 181-183.

O' Connell, MG, O'Leary, GJ & Incerti, M 1996. Potential groundwater recharge from fallowing in northwest Victoria, Australia. *Agricultural-Water-Management* 29: 37-52 (abstract).

O'Connor, TG 1985. A synthesis of field experiments concerning the grass layer in the savanna regions of southern Africa. Report No 114, South African National Scientific Programmes, Foundation for Research Development, Pretoria.

O'Keeffe JH (ed.) 1986. The conservation of South African rivers. South African National Scientific Programmes Report No. 131, FRD, Pretoria.

Pate, JS, Jeschke, WD & 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.

Peck, AJ & Williamson, DR 1987. Effects of forest clearing on groundwater. *Journal of Hydrology* 94: 47-66.

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

Prebble, RE & Stirk, GB 1980. Throughfall and stemflow on silverleaf ironbark (*Eucalyptus melanophloia*) trees. *Australian Journal of Ecology* 5: 419-427.

Pressey, RL 1986. Wetlands and catchment management. *Journal of Soil Conservation of New South Wales* 42: 36-41.

Pressland, AJ 1973. Rainfall partitioning by an arid woodland (*Acacia aneura* F. Muell.) in south-western Queensland. *Australian Journal of Botany* 21-235-245.

Rawlins BR and Kelbe, BE, 1991. Case study on the hydrological response of a shallow coastal aquifer to afforestation. In: *Hydrological basis of ecologically sound management of soil and groundwater.* Proc. Symp., Vienna, Aug. 1991. IAHS Publ. 202, 1991, pp. 357-366.

Rhoades, CC 1997. Single-tree influences on soil properties in agroforestry: lessons from natural forest and savanna ecosystems. *Agrofroestry Systems* 35: 71-94.

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

Richardson, SB & Narayan, KA 1996. The effectiveness of management options for dryland salinity control at Wanilla, South Australia. *Agricultural Water Management* 29: 63-83 (abstract).

Rickard. WH & Price. KR 1989. Uptake of tritiated groundwater by black locust trees. *Northwest Science* 63: 87-89 (Abstract).

Rogers, KH 1995. Riparian wetlands. In: Wetlands of South Africa (ed. GI Cowan). Department of Environment Affairs and Tourism, Pretoria.

Rogers, KH & Higgins, SI 1993. The Nyl floodplain as a functional unit of the landscape: preliminary synthesis and future research. Report 1/93, Centre for Water in the Environment, University of the Witwatersrand, Johannesburg.

Rood, SB and Mahoney, JM 1990. The collapse of riparian poplar forests downstream from dams on the western prairies: probable causes and prospects for mitigation. *Environmental Management* 14: 451–464.

Roose, E 1981. Dynamique actuelle de sols ferralitiques et ferrigineux tropicaux d'Afrique Occidentale. Trav Doc ORSTOM 130: 569, ORSTOM, Paris.

Rundel, PW, Nobel, PS & Atkinson D 1991. Structure and function in desert root systems. In: *Plant root growth: an ecological perspective*. pp. 349-378. British Ecological Society Special Publication, No. 10 (abstract).

Ruprecht, JK & Stoneman GL 1993. Water yield issues in the jarrah forest of Western Australia. *Journal of Hydrology* 150: 361-391.

Rutherford, MC 1980. Field identification of roots of woody plants of the savanna ecosystem study area, Nylsvley. *Bothalia* 13: 171-184.

Rutherford, MC 1983. Growth rates, biomass and distribution of selected woody plant roots in *Burkea africana - Ochna pulchra* savanna. *Vegetation* 52: 45-63.

Rutherford, MC & Westfall, RH 1996. Biomes of southern Africa - an objective categorisation. Memoirs of the Botanical Survey of South Africa No. 54. Department of Agriculture and land Affairs, Pretoria.

Sahai, B, Sood, RK & Sharma, SC 1985. Groundwater exploration in the Saurashtra peninsula. *International Journal of Remote Sensing* 6: 433-441.

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.

Salama, RB, Farrington, P, Bartle, GA & Watson, GD 1993a. The chemical evolution of groundwater in a first-order catchment and the process of salt accumulation in the soil profile. *Journal of Hydrology* 143: 233-258.

Salama, RB, Farrington, P, Bartle, GA & Watson, GD 1993b. Salinity trends in the wheatbelt of Western Australia: results of water and salt balance studies from Cuballing catchment. *Journal of Hydrology* 145: 41-63.

Sarmiento, G & Monasterio, M 1983. Life-forms and phenology. In: *Tropical savannas*. Ecosystems of the World Vol 13 (ed. Bourliere, F), pp 79-108. Elsevier, Amsterdam.

Schofield, NJ 1990. Determining reforestation area and distribution for salinity control. *Hydrological Sciences Journal* 35: 1-19.

Schofield, NJ & Bari, MA 1991. Valley reforestation to lower saline groundwater tables: results from Stene's farm, Western Australia. *Australian Journal of Soil Research* 29: 635-650.

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

Scholte, PT 1989. Vegetation soil relations in an area with sealed chronic luvisols, Kenya. *Arid Soils Res Rehabilitation* 3: 337-348.

Schot, PP & Wassen, MJ 1993. Calcium concentrations in wetland groundwater in relation to water sources and soil conditions in the recharge area. *Journal of Hydrology* 141: 197-217.

Schulze, E-D, Mooney, HA, Sala, OE, Jobbagy, E, Buchmann, N, Bauer, G, Canadell, J, Jackson, RB, Loreti, J, Oesterheld, M & Ehleringer, JR 1996. Rooting depth, water availability and vegetation cover along an aridity gradient in Patagonia. *Oecologia* 108: 583-595.

Schulze, RE 1981. The land use component in hydrological modelling: an evaluation. In: Workshop on the effect of rural landuse and catchment management on water resources (ed. H Maaren). Technical report TR 113 pp 34-61, Department of Water Affairs, Forestry and Environmental Conservation, Pretoria.

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, Scott Shaw, CR & Nänni 1978. Interception by Pinus radiata in relation to rainfall parameters. *Journal of Hydrology* 36: 393-396.

Schwinzer, CR and Lancelle, SA. 1983. Effect of water table depth on shoot growth, root growth, and nodulation of *Myrica gale* seedlings. *Journal of Ecology* 71: 489-501.

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, 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 and Smith, RE, 1997. Preliminary empirical models to predict reductions in annual and low flows resulting from afforestation. *Water SA 23: 135-140.*

Scott, JD & Van Breda, NG 1937a. Preliminary studies of the root system of the renosterbos (*Elytropappus rhinocerotis*) on the Worcester veld reserve. *South African Journal of Science* 34: 560-569.

Scott, JD & Van Breda, NG 1937b. Preliminary studies of the root systems of *Galenia africana* on the Worcester veld reserve. *South African Journal of Science* 34: 268-274.

Scott, JD & Van Breda, NG 1938. Preliminary studies of the root systems of *Pentzia incana-forma* on the Worcester veld reserve. *South African Journal of Science* 35: 280-287.

Scott, JD & Van Breda, NG 1937b. Preliminary studies of the root systems of *Euphorbia mauretanica. E. burmanni* and *Ruschia multiflora* on the Worcester veld reserve. *South African Journal of Science* 36: 227-235.

Sharma, ML & Craig, AB 1989. Comparative recharge rates beneath *Banksia* woodland and two pine plantations on the Gnangara mound, Western Australia. In: *Groundwater recharge* (ed. ML Sharma), pp 177-184. AA Balkema, Rotterdam.

Sharma, ML, Bari, M & Byrne, J 1991. Dynamics of seasonal recharge beneath a semiarid vegetation on the Gnangara Mound, Western Australia. *Hydrological Processes* 5: 383-398.

Sharma, ML, Barron, RJW & Craig, AB 1991. Land use effects on groundwater recharge to an unconfined aquifer. Divisional Report - Division of Water Resources, CSIRO (abstract).

Sharma, ML, Barron, RJW & Williamson, DR 1987a. Soil water dynamics of lateritic catchments as affected by forest clearing for pasture. *Journal of Hydrology* 94: 29-46.

Sharma, ML, Barron, RJW & Fernie, MS 1987b. Areal distribution of infiltration parameters and some soil properties in lateritic catchments. *Journal of Hydrology* 94: 109-127.

Sharma, ML, Farrington, P & Fernie, M 1983. Localised groundwater recharge on the "Gnangara Mound", Western Australia. International Conference on Groundwater and Man, Sydney, 5-9 December 1983, pp 293-302. Conference Series No 8, Australian Water Resources Council, Government Publisher, Canberra.

Sherry, SP 1971. The black wattle (*Acacia mearnsii* De Wild.). University of Natal Press, Pietermaritzburg.

Slatyer, RO 1961. Methodology of a water balance study conducted on a desert shrubland (*Acacia aneura* F. Muell.) community in central Australia. Proceedings of the Symposium on plant water relationships in arid and semi-arid conditions. UNESCO, Paris.

Slatyer, RO 1965. Measurement of precipitation, interception by an arid plant community (*Acacia aneura* F. Muell.) *Arid Zone Research* 25: 181-192.

Sililo, OTN & van der Voorte, I, 1996. *Hydrogeological investigation of the Blouvlei site*. Report no 5/96. CSIR Division of Water, Environment and Forestry Technology, Stellenbosch.

Smith, SD, Wellington, AB, Nachlinger, JL & Fox, CA 1991. Functional responses of riparian vegetation to streamflow diversion in the eastern Sierra Nevada. *Ecological Applications* 1: 89-97.

Snyman, HA 1988. Bepaling van waterverbruiksdoeltreffendheid van veld in die sentrale Oranje-Vrystaat vanaf evapotranspirasiemetings. *Water SA* 14: 153-158.

Specht, RL & Rayson, P 1957. Dark Island heath (Ninety-mile Plain, South Australia). III. The root systems. *Australian Journal of Botany* 5: 103-114.

Specht RL 1957. Dark Island Heath (Ninety Mile Plain, South Australia). IV. Soil moisture patterns produced by rainfall interception and stemflow. *Australian Journal of Botany* 5: 137-150.

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

Stephens, DB 1994. A perspective on diffuse natural recharge mechanisms in areas of low precipitation. *Soil Science Society of America Journal* 58: 40-48.

Stone EL & Comerford, NB 1994. Plant and animal activity below the solum. Whole regolith pedology: Proceedings of a symposium, Minneapolis, Minnesota, 3 Nov. 1992, pp 57-74 (abstract).

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

Stoneman, GL 1993. Hydrological response to thinning in a small jarrah (*Eucalyptus marginata*) forest catchment. *Journal of Hydrology* 150: 393-407.

Strang, RM 1969. Soil moisture relations under grassland and under woodland in the Rhodesian highveld. *Commonwealth Forestry Review* 48: 26-40.

Stringer, JW, Kalisz, PJ & Volpe, JA 1989. Deep tritiated water uptake and predawn xylem water potentials as indicators of vertical rooting extent in a Quercus-Carya forest. *Canadian Journal of Forest Research* 19: 627-631 (abstract).

Stromberg, JC 1993. Instream flow models for mixed deciduous riparian vegetation within a semi-arid situation. *Regulated Rivers: Research & Management* 8: 225-235.

Stromberg, JC, Tiller, R and Richter, B 1996. Effects of groundwater decline on riparian vegetation of semiarid regions: the San Pedro, Arizona. *Ecological Applications* 5: 113-131.

Stromberg, JC, Wilkins, SD and Tress, JA 1993. Vegetation-hydrology models: implications for management of *Prosopis velutina* (velvet mesquite) riparian ecosystems. *Ecological Applications* 3: 307-314.

Suso, J & Llamas, MR 1993. Influence of groundwater development on the Doñana National Park ecosystems (Spain). *Journal of Hydrology* 141: 239-269.

Taakspan LWSK, 1989. Invloed van grondwater onttrekking op karoo-ekologie: Verslag van wetenskaplike taakspan aan LWSK. Technical report, no GH 3630, Department of Water Affairs and Forestry.

Talsma, T & Gardner, EA 1986a. Soil water extraction by a mixed eucalypt forest during a drought period. *Australian Journal of Soil Research* 24: 25-32.

Talsma, T & Gardener, EA 1986b. Groundwater recharge and discharge response to rainfall on a hillslope. *Australian Journal of Soil Research* 24: 343-356.

Tarboton WR 1987. The Nyl floodplain: its significance, phenology and conservation status. In: Symposium: Ecology and conservation of wetlands in South Africa (eds RD Walmsley & ML Botten), pp 101-114. Occasional Report No. 28, CSIR, Pretoria.

Ter Hoeve, J 1978. Precipitation and replenishment of groundwater in wooded areas. *H2O (Rotterdam)* 11: 364-368. (in Dutch)

Theron, JJ< 1964. Lesimiterprowe II: 1945-1961. *South African Journal of Agricultural Science* 7: 109-122.

Thorburn, PJ & Ehleringer, JR 1995. Root water uptake of field-growing plants indicated by measurements of natural-abundance deuterium. *Plant and Soil* 177: 225-233 (abstract).

Thorburn, PJ & Walker, GR 1993. The source of water transpired by *Eucalyptus camaldulensis*: soil, groundwater or streams? In: Stable isotopes and plant carbon-water relations (eds JR Ehleringer, AE Hall & GD Farquhar), pp 511-527. Academic Press Inc., San Diego.

Thorburn, PJ & Walker, GR 1994. Variations in stream water uptake by *Eucalyptus camaldulensis* with differing access to streamwater. *Oecologia* 100: 293-301.

Thorburn, PJ, Cowie, BA & Lawrence, PA 1991. Effect of land development on groundwater recharge determined from non-steady chlorine profiles. *Journal of Hydrology* 124: 43-58.

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.

Tolman, M 1989. Transpiraiton des essences principales dans le periode mars-mai 1989, dans le quatre basins versants. IWACO, Ouagadougou, Burkina Faso/Univ Groningue, Groningen.

Travis, KA & Heuperman, AF 1994. Agroforestry - checkbank plantings. Technical Report Series No 215, Institute of Sustainable Irrigated Agriculture, Victorian Department of Agriculture, Australia.

Tromble, JM 1977. Water requirements for mesquite (*Prosopis juliflora*). *Journal of Hydrology* 34: 171-179.

Tyler, SW & Walker, GR 1994. Root zone effects on tracer migration in arid zones. *Soil Science Society of America Journal* 58: 25-31.

Ullman, I 1985. Diurnal courses of transpiration and stomatal conductance of Sahelian and Saharian acacias in the dry season. *Flora* 176: 383-409. (in German, English abstract)

Valentini, R, Scarascia Mugnozza, GE, De Angelis, P & 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 Breda, PAB & Barnard SA 1991. *100 Veld plants of the winter rainfall region*. Bulletin No 422, Department of Agricultural Development, Pretoria.

Van Lanen, HR 1978. Some notes on the relation between precipitation and groundwater recharge in wooded areas. *H2O (Rotterdam)* 11: 522-523 (in Dutch).

Van Noordwijk, M 1984. *Ecology textbook for Sudan.* Ecol Uitgeverij, Amsterdam.

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

Van Wyk, DB, 1987 Some effects of afforestation on streamflow in the Western Cape Province, South Africa. *Water SA* 13: 31-36.

Van Wyk, E., 1997 Kathu Impact Study. Internal departmental memo, P313, 21 January 1997. Directorate of Geohydrology, Dept of Water Affairs and Forestry.

Van Wyk, WL, 1963, Ground-water studies in northern Natal, Zululand and surrounding areas. Geological Survey of South Africa Memoir no. 52.

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.

Vegter, JR, 1993. Effect of clearing arid sweet bushveld vegetation on Groundwater, Northwestern and Northern Transvaal. Unpublished consultancy report, No. GH3811, to Directorate of Geohydrology, Dept of Water Affairs and Forestry, Pretoria.

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

Vegter JR and Pitman, WV, 1996. Recharge and streamflow. Paper presented at the workshop: Groundwater - Surface Water Issues in Arid and Semi-arid Areas, Warmbaths, October, 1996. Water Research Commission, Pretoria.

Versfeld, DB 1988. Rainfall interception in stands of *Pinus radiata* and *Protea nerifolia*. In: Research contributions to plantation forestry. Festschrift in honour of Prof. A. van Laar, pp 130-149. Forestry Faculty, University of Stellenbosch.

Versfeld, DB, Everson, CS & Poulter, AG, 1997. The use of vegetation in the amelioration of the impacts of mining on water quality - an assessment of species and water use. Unpublished contract report to the Water Research Commission, Report ENV/S-C 97147, CSIR Division of Environment, Water and Forestry Technology, Pretoria.

Viljoen, AJ 1995. The influence of the 1991/92 drought on the woody vegetation of the Kruger National Park. *Koedoe* 38: 85-97.

Von Hoyningen-Heune, J 1983. Die interzeption des Niederschlages in landswirtschaftlichen Planzenbeständen. Deutscher Verband für Wasserwirtschaft und Kulturbau. Schriften 57 pp. 1-66, Verlag Paul Parey-Hamburg, Germany.

Von Maydell, H-J 1986. *Trees and shrubs of the Sahel. Their characteristics and uses.* GTZ, Eschborn, Germany.

Walmsley RD 1988. A description of the wetlands research programme. South African National Scientific Programmes Report No. 145, FRD, Pretoria.

Walter, H 1973. *The vegetation of the earth in relation to climate and the eco-physiological conditions.* Springer-Verlag, Berlin.

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.

Wessolek, G, Reents, HJ, Moller, W & Muller, P 1994. Interpretation of vertical nitrate depth profiles of sandy soils with different utilization. *Zeitschrift fur Kulturtechnik und Landentwicklung* 35: 10-20 (abstract; paper in German).

Westfall, RH & Drewes, R 1984. Grass root pattern in an Orange Free State floodplain. *Bothalia* 15: 293-295.

Westfall, RH & van Staden, JM 1996. Primary divisions of the biomes of South Africa. *South African Journal of Science* 92: 373-375.

Whitfield, DM, Heuperman, AF, Prendergast, JB, Newton, PJ, Mann, L & Starke, R undated. Final Report: Irrigated Agroforestry. DRDC Project DAVI89, NRMS Project VI56, Department of Agriculture, Australia.

Wickens, GE 1980. Alternative uses of browse species. In: *Browse in Africa: the current state of knowledge*. Papers presented at the International Symposium on Browse in Africa, Addis Ababa (ed. HN Le Houerou), pp 155-182. ILCA, Addis Ababa.

Williamson, DR 1990 Salinity - an old environmental problem. Technical Memorandum No. 90/7 - Division of Water Resources, Institute of Natural Resources and Environment, CSIRO (abstract).

Williamson, DR, Stokes, RA & Ruprecht, JK 1987. Response of input and output of water and chloride to clearing for agriculture. *Journal of Hydrology* 94: 1-28.

Wiseman, K 1996. Strategic environmental assessment (SEA). A primer. CSIR Report ENV/S-RR 96001, Division of Water, Environment and Forest Technology, CSIR.

Young, JA, Evans, RA & Easi DA 1984. Stem flow on western Juniper (*Juniperus occidentalis*) trees. *Weed Science* 32: 320-327.

Zoth, R & Block, J 1992. Investigations on the root balls of windthrown trees in Rhineland-Palatinate. *Forst und Holz* 47: 566-571 (abstract).

APPENDIX:
PROCEEDINGS OF A WORKSHOP

Venue: Nylsvley Nature Reserve

Date: Tuesday and Wednesday 10 and 11 September, 1996

Delegates: Mr JR Vegter, Private Groundwater Consultant
Messrs Hugo Maaren and Tony Reynders, Water Research Commission.
Mr Eberhard Braune, Directorate of Geohydrology, Dept of Water Affairs
Mr Brian Rawlins, University of Zululand Hydrologist
Messrs John Weaver and Reinie Meyer, CSIR Geo-hydrologists
Mr David Le Maitre, CSIR, Stellenbosch Plant ecologist
Dr Peter Dye, CSIR, Nelspruit Tree physiologist
Dr Dave Scott, CSIR, Stellenbosch Forest hydrologist

Objective of the Workshop

To categorise and roughly quantify the vegetation-groundwater interactions in southern Africa, identify research needs in this field, and develop a research strategy.

Inputs

Draft technical review based on literature review, interviews and anecdotal information.

Outputs

Draft research strategy document

Programme followed

Day 1:

0. Welcome and introduction

1. Agreement on objective of the meeting

2. Agreement on how to go about working toward our goal

3. Cursory overview of world literature. David Le Maitre

4. Review of Southern African case studies:-

Brief summary of the afforestation experiments (catchments)	Dave Scott
Deep rooting by plantation trees in Mpumalanga	Peter Dye
Pine plantations on the Zululand sand flats	Brian Rawlins
The effect of bush clearing on groundwater levels	JR Vegter
The effect of vegetation on recharge of the Atlantis aquifer	John Weaver
The De Aar well-fields' effects on karroo ecology	JR Vegter
Geo-technical problems associated with clearing vegetation	Dave Scott
Venetia Mine and groundwater pumping on the Limpopo	Dave Scott

5. Presentation of the big picture of groundwater resources and regions in South Africa. JR Vegter

Day 2:

6. Types of vegetation - groundwater interaction: conceptual models

7. What are the research issues in South Africa

8. Prioritising of the various research issues

CLASSIFYING TYPES OF VEGETATION-GROUNDWATER INTERACTIONS

The table below describes a possible classification of vegetation groundwater interactions from a groundwater resource perspective, in which the importance of the potential role of vegetation in affecting recharge is ranked. The rationale behind this classification is that where the groundwater resource is large, and where the soil profile available water is high, the role of vegetation will assume greater importance. The size of the role of vegetation (size of recharge reduction caused by a vegetation type) is not incorporated.

Recharge Potential		**High Profile Available Water Capacity**		**Low Profile Available Water Capacity**	
		Large aquifer capacity	*Small aquifer capacity*	*Large aquifer capacity*	*Small aquifer capacity*
Potential Recharge is High	*Dependable (low variability)*	1 *	2	2	3
	Erratic (high variability)	2	3	3	4
Potential Recharge is Low	*Dependable*	1	2	2	3
	Erratic	2	3	3	4

* **Vegation Importance Ranking:** 1. = Role of vegetation is very important, 4. = Role of vegetation is insignificant.

Classification from the point of view of plants:- (David Le Maitre and J R Vegter)

Plants using water from vadose zone	Plants using water from Saturated Zone
	Phreatic vs Non-phreatic plants
	Evaporative vs Surface water wetlands
	Phreatic Vegt: Alluvial aquifers vs Bedrock rivers

This classification is in terms of, firstly, the vulnerability of vegetation communities to negative effects of groundwater exploitation (A - plants in discharge zones) and, secondly, the potential of different forms of vegetation to affect groundwater recharge (B - plants in recharge areas).

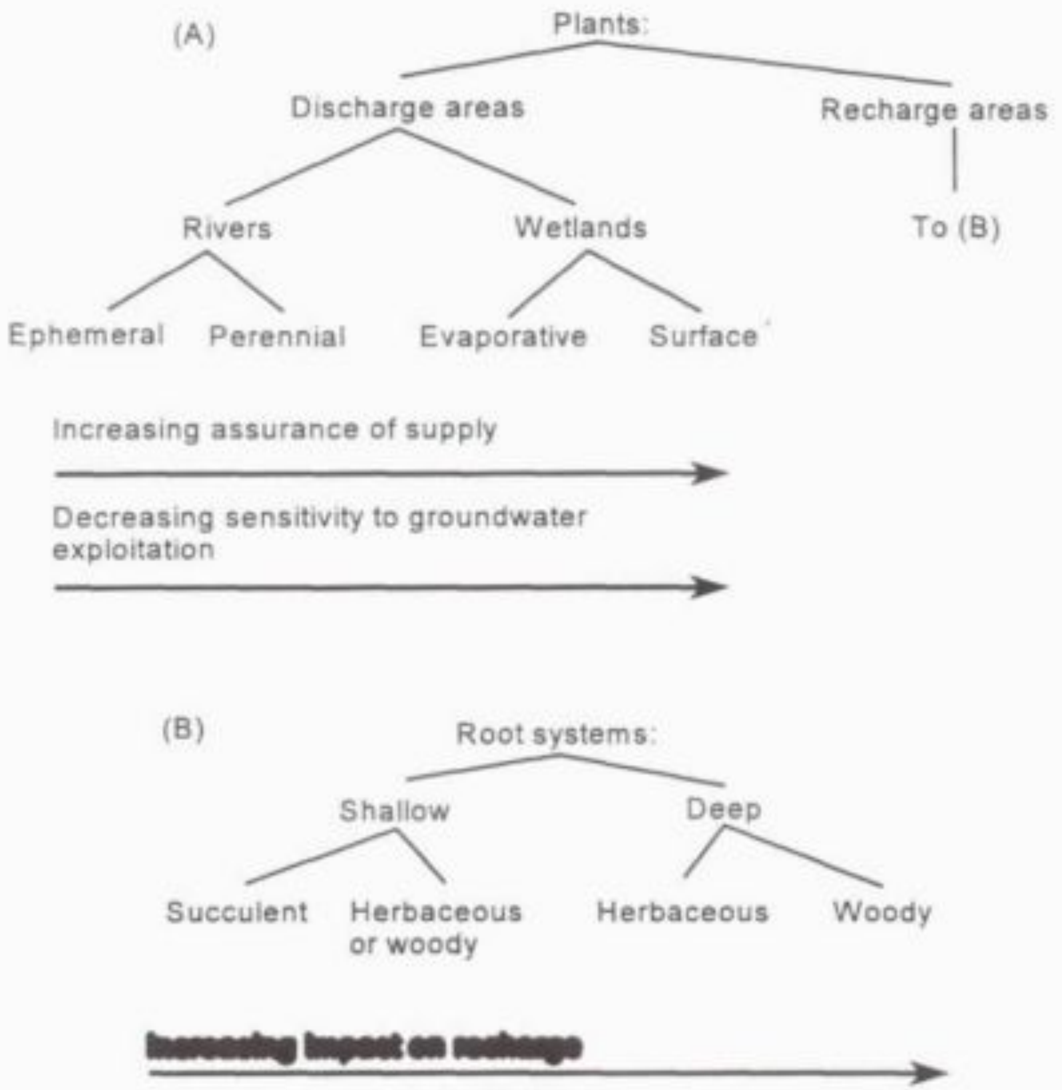

Figure 1: A simplified diagram of the relationships between groundwater dynamics, and plant attributes showing their sensitivity to changes in groundwater levels and likely impacts on recharge.

Classification (Hugo Maaren)

Physical Landscape: Hydrologic Classification	Human Intervention	
	Change Vegetation	**Change Abstraction** (add discharge)
Hard rock		
Alluvial Rivers		
Coastal Sands		

Hugo Maaren 2:

Source areas vs Sink areas

Hugo Maaren 3:

Graphic of Storage capacity on vertical axis and Rainfall on horizontal. As storage increases and rainfall decreases, so one would tend to have a groundwater system dominated by vertical movement; as one moves to opposite quadrant so flow becomes dominated by lateral flow.

John Weaver:

Affect of G/w water-table on Vegt. (Structure of a manual on vegetation water use)

1. Vegetation is independent (no direct contact) with g/water (e.g. grass)
2. Vegetation either dependent or independent
3. Totally dependent (obligate phreatophytes)
4. Exceptional cases: acacias in the Kuiseb (opportunists)

How do these various types affect hydrology

Vegetation affecting groundwater

- vegetation effects on groundwater
- vegetation effects on abstractions from groundwater

Tony Reynders

Landscape Units - Groundwater Systems

Water Balance Classification for Key Landscapes (Peter)
i.e. Rain into Vadose zone - drains to groundwater - discharge from groundwater; Minus abstractions (by plants primarily) of vadose zone water and groundwater.

Reinie Meyer

Control exerted by geology / hydrogeological system
Recharge vs demand (e.g. if recharge is high relative to demand)
Water balance within a regional system, or within a localised "compartments"
Recharge process within unsaturated zone
Land use effects

Brian Rawlin's Hierarchical Classification System

Recharge is High or Low (Recharge Axis)
Broad Geological type
Hydrogeological characteristics (depth to water, depth, porosity, permeability)
Groundwater use characteristics:
- total reliance on g/w
- auxiliary source of water
- not used (as groundwater)

Surface hydrology
- Reliance on groundwater

Vegetation:
- is it dependent or independent of groundwater

Is the ecology (system)
- unique (rating of uniqueness)
- sensitive to small changes or not
- stable

Dave Scotts's Figure 2 attempts to illustrate the generalised relationship between broad vegetation types and potential for groundwater recharge. Annual rainfall is a powerful determinant of possible vegetation types, and also of the potential water surplus (P-E) that can become recharge. At lowest rainfalls vegetation is restricted to karoo types, potential evaporation far exceeds rainfall and recharge will be limited to rare high rainfall events. Grasslands occur over a broad rainfall range, and at the higher rainfall sites there is a large potential for recharge to occur. Savanna, woodland and thicket occur over a similar rainfall range to grasslands, but evaporative losses will generally be higher than under grassland, and the potential for recharge consequently lower. Areas in South Africa with a high rainfall of high dependability may carry indigenous forest or may be afforested with timber species. These tall evergreen vegetation types with a high leaf area and high stomatal conductance, reduce the recharge potential that the same sites would have under the alternative vegetation types of grassland or fynbos. Plantations of exotic timber species have a high productivity and high transpiration rates, and consequently reduce recharge the most.

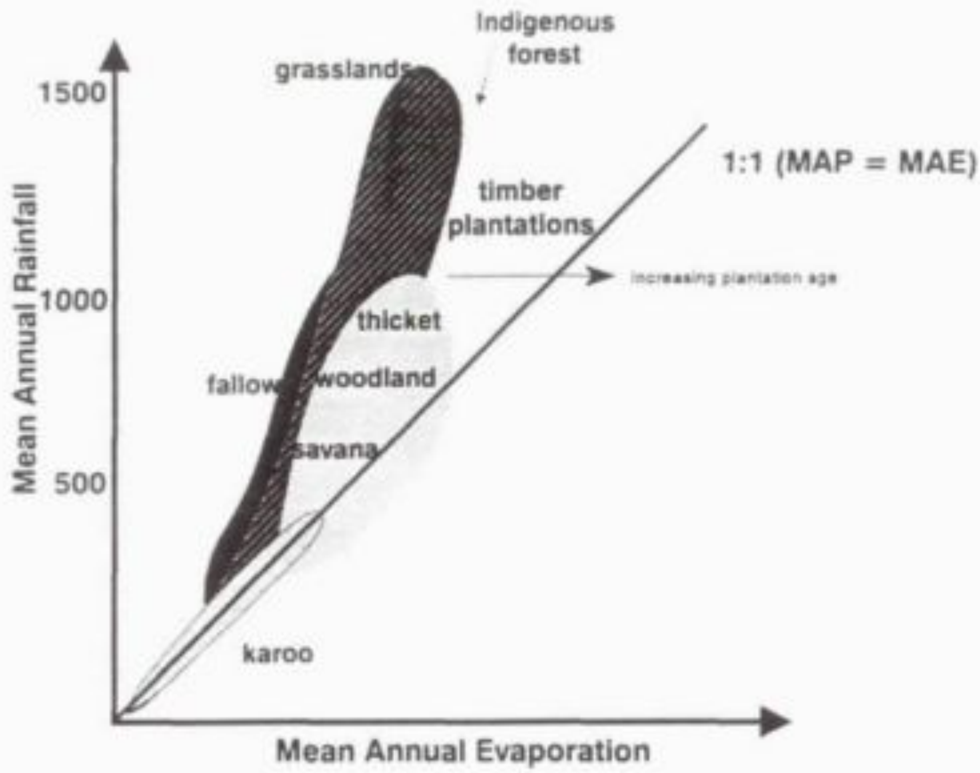

Figure 2: Envelopes showing hypothesised potential recharge within the different biomes in South Africa, mean annual rainfall (mm) and evaporation. Recharge will only occur on an annual or semi-annual basis above the line where MAP = MAE. Shading below the 1:1 line indicates a net loss of water from storage.

RESEARCH ISSUES AND PRIORITIES

One of the sessions at the Nylsvley Workshop was aimed at creating a summary of the most important issues requiring research, based on the presentations, discussions and the participants, research and experience. The issues raised during this session are summarised in this section. They have been grouped into a set of broad categories based on the major research areas that they address. The relationships between the different research areas is indicated in Figure 3. The different sections below are arranged roughly in order of the scale at which they address the issues from broad to detailed. The priorities for research are discussed in section: Research Priorities.

Research Issues

(i) ***Support for policy and planning relating to groundwater resources***

The legislation and policy relating to the management of South Africa's scarce and valuable water resources is currently being revised. This revision involves a number of significant changes. These include the revision of national policy on the utilisation and management of water resources and the Water Act. The new policy recognises that all water (ground and surface) is part of the water cycle and therefore interconnected. It also requires the utilisation of all water resources to be sustainable both in terms of the yield to the users and the potential impacts of abstraction on other users and the environment. The new approach has also shifted the emphasis in water supply to the provision of water to the formerly neglected rural population, an important shift because many of these communities depend entirely on groundwater. Effective implementation of the new policies and legislation will require sound information on the available groundwater resources. This information will have to come from research. The next section discusses some of the planning tools which are being used or developed to ensure that groundwater resources are used equitably and sustainably and which will require information from research to be effective.

Integrated catchment management

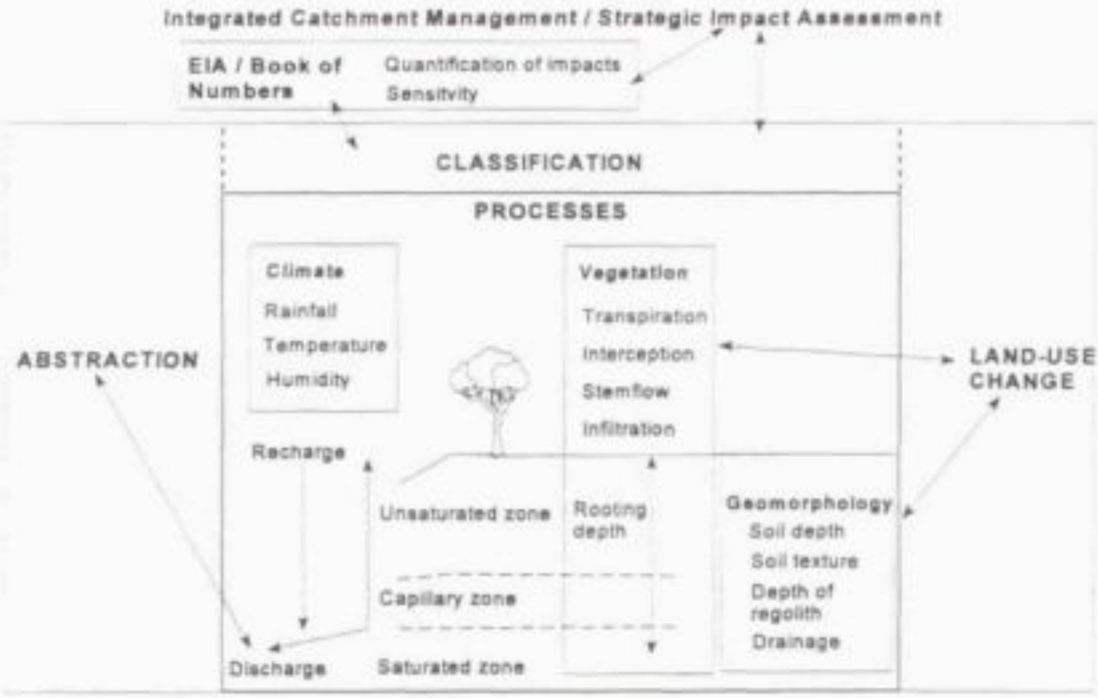

Figure 3: A conceptual framework for the research issues in the area of groundwater-vegetation interactions.

In the past, developments in catchments were typically undertaken in isolation with little or no consultation with many of the parties likely to be affected, especially indirectly, by those developments. The new approaches adopted towards policy and planning under the former Reconstruction and Development Programme require the participation of all the stakeholders in the resources of that catchment. Developments in catchments have to be evaluated in terms of their potential impacts on water yield, water quality, socio-economic factors and nature conservation and the goal of sustainable development. The Integrated Catchment Management (ICM) process of policy, planning, implementation and monitoring therefore provides the context for the planning and management of groundwater use (what, where, when and how) and must also guide research.

Strategic Environmental Assessment

Strategic Environmental Assessment (SEA) is a new approach to policy and planning which addresses many of the weaknesses inherent in the present fragmented approach, especially the failure to address environmental issues effectively. The aims of SEA are to ensure that environmental issues are addressed in a proactive way at a broad stake, in policies and plans, to improve the assessment of the cumulative impacts of developments on the environment, and to focus on achieving sustainable development (Wiseman 1996). As it is an issues driven and participative approach to environmental matters, this approach will be a key component of ICM. The tools that will be needed to make SEA effective in this context will include groundwater resource assessment and hydrological-environmental impact sensitivity analysis and mapping.

Environmental Impact Assessment (EIA) complements SEA when it comes to addressing the environmental aspects of individual projects. There is increasing recognition that EIAs are often too narrowly focussed and fail to address issues relating to the ripple effects of the projects in both space and time. This is potentially an important weakness when it comes to groundwater resources where the effects of, for example, abstraction at one point may be experienced at points far "downstream". This weakness is the focus of Cumulative Effects Assessment which is specifically aimed at addressing the "ripple effects" of particular developments.

Climate change

Climatic change has important implications for groundwater resources in South Africa. If climate changes resulted in increasing severity of drought cycles then this could have severe impacts on communities dependant on the very limited groundwater resources that are available. Thus the implications of climate change need to be considered if the issue of sustainability is to be addressed effectively. At this stage a simple summary of the hydrological implications would suffice and is, in any case, about as much as can be expected from the current models.

Capacity building

There are few hydrogeologists, botanists or ecologists in South Africa who have carried out research on groundwater-vegetation interactions. Capacity building therefore should also focus on building inter-disciplinary skills to facilitate the trans-disciplinary work that is needed to support the sustainable utilisation of groundwater resources.

(ii) *Classification system*

A basic requirement for research on groundwater-vegetation interactions is a national overview of the kinds of interactions and the driving factors that determine their occurrence in space and their importance. There is probably no one system that will meet all needs and the scheme below is suggested as a beginning point.

The aim is to provide a classification scheme and maps of hydrological landscape types in South Africa which are designed for use by policy makers, planners and managers and scientists from other disciplines.

The first step will require an analysis of the existing data in order to define and delineate geo-hydrological response zones, and geo-hydrological response units within these. Potentially suitable data sets include: maps of the vegetation (Acocks 1953; Low & Rebelo 1996), groundwater resources (Vegter 1995), land-types (ICSW), topography (Directorate of Mapping and Survey), climate (CCWR) and surface water resources of South Africa (Midgley *et al.* 1994) in Geographic Information System format. In addition there are classifications of wetlands (Cowan 1995b) and river systems (Davies *et al.* 1993) which may provide useful information.

The following factors will need to be addressed:

- Groundwater - vegetation interactions, especially the impacts on recharge and extraction of water from the unsaturated and saturated zones.
- Groundwater - surface water relationships, especially the importance of recharge and discharge in riparian zones.

Some of the aspects that will need to be considered in the data collection and analysis:

- Analysis of regional and other patterns in recession curves as an indicator of groundwater storage and flux rates.
- Analysis of the frequency and variability of groundwater recharge and how this propagates through to discharge.
- The use of GIS to gather, prepare, process and store the appropriate data (making maximum of use of data sets that are already available). This will enable the data base to be made widely available and will simplify and facilitate updating of the handbook.

(iii) ***Effects of land use changes on groundwater***

A research programme will be needed to address the many gaps in our understanding of groundwater-vegetation interactions and their dynamics. In addition there is very little reliable information on the importance of the different processes in the South African situation. Thus the studies in this section are divided into two interrelated groups: studies of the processes themselves and studies aimed at providing quantitative data.

Process studies

- Effects of vegetation on recharge in the South African context including:
  - matrix vs macropore flow
  - deep roots as channels
  - partitioning of rainfall into interception, transpiration, stemflow, infiltration
  - effects of rooting depth
    - → use of unsaturated (vadose) zone only
    - → use of unsaturated and saturated zone
    - → start a programme of detailed case studies on representative hydrological response units (this will have to be tightly co-ordinated with studies under **Classification** above)

Quantification

These studies would be aimed at identifying gaps in our quantitative understanding of factors involved in groundwater-vegetation interactions. A key aim of this research is to provide information needed to develop the *Book of Numbers* (see iv below).

- Rooting depths by veg classes (major types):
  - maximum depths
  - effective "pumping depths"
- Water consumption by crops, grass, bushveld etc:
  - relation between aerial biomass and infiltration and recharge
  - quantify effect of bush-clearing
  - vegetation changes that quantify and typify:
    - → increase recharge
    - → decrease recharge

- quantify potential for modification of groundwater and surface water systems by vegetation modification (maximum yields, recharge etc.)
- identify:
  - → species that increase recharge
  - → woodlot species for social and agroforestry tree planting programmes that do not deplete groundwater resources
- determine changes in evapotranspiration rates following land-use and vegetation cover change
- characterise South African vegetation types in terms of their potential to affect recharge in different areas
- develop guidelines for water requirements and water-use of vegetation to put into a *Book of Numbers* for groundwater specialists to use in EIA's and other groundwater resource assessments.
- effects of riparian zone vegetation changes (alien plant removal) on hydrological system.

(iv) ***Book of Numbers***

There is a need for a compendium of existing information on relationships between vegetation water-use, rainfall, evapotranspiration and land-use types in South Africa, for use in planning groundwater use and in groundwater impact assessments. This compendium or handbook has been provisionally named the *Book of Numbers*. The following issues should be considered, in addition to the quantification studies suggested in the preceding section (iii. *Effect of land use changes*).

➢ The need to provide guidelines on estimating the groundwater ecological reserve needed to ensure that ecosystems are not adversely affected.

➢ The issue of how to factor in rainfall variability and its propagation through the groundwater-vadose zone-surface water system in groundwater resource assessment.

➢ The impact of industrial or urban development on groundwater resources needs to be addressed (this is considered a peripheral issue at present).

➢ Vegetation or terrestrial habitat vulnerability and ecological significance.

(v) ***Impacts of groundwater abstraction (exploitation) on vegetation***

Groundwater abstraction plainly can, and does, have impacts on vegetation communities. There is a need for research projects to address both the impacts and the techniques for rehabilitation. Research should address *inter-alia* the following topics and should aim at producing guidelines for water resource planners and managers:

➢ Identify what makes different ecosystems more or less sensitive to groundwater abstraction and quantify the importance of each type. A logical, place to start would be to do more detailed investigations of the cases where vegetation damage was, or could be, attributed to declining groundwater levels.

➢ Analyse the effects of water abstraction from springs on sponges and vlei areas that they are connected to.

➢ Research methods to control, moderate and reverse the detrimental effects of past vegetation modifications.

(vi) ***Hillslope hydrology***

Hillslope hydrology is the study of the role of factors such as lithostratigraphy, geomorphology and soils (depths, hydraulic conductivities) on the interactions between surface and subsurface fluxes of water. Although work has been done on typifying the hydrological properties of South African soils and on large scale land-types (which relate soils to geology and geomorphology) this work has not yet been integrated with vegetation patterns. Research in this area needs to address the following topics:

- The dynamics of water movement in South African landscapes, especially to unify soil-plant-atmosphere interactions with hydrogeology.

- The development or refinement of techniques to characterise soil/subsoil profile water movement and calculate storage capacity in both the unsaturated and saturated zones, including the capillary fringe.

- Studies of unsaturated zone processes related to vegetation that can materially alter groundwater recharge, including:
  - the importance of macropores and the role of woody plants in concentrating water through stemflow and of their root channels as macropores;
  - effects of moisture depletion by transpiration in this zone on recharge rates and amounts;
  - characteristics that determine whether it has a high or low soil water storage capacity, particularly in savanna systems; and
  - role of unsaturated zone water in maintaining riparian vegetation.

- The role of groundwater in sustaining wetlands, estuaries and other systems directly or indirectly dependent on groundwater.

(vii) ***Phreatic vegetation***

- The identification and management of phreatic vegetation types, especially in savanna:

  - characterising and understanding the dynamics and structure of vegetation overlying:
    - → bedrock aquifer systems
    - → alluvial aquifer systems;
  - plant rooting behaviour and adaptability in alluvial and bedrock systems;
  - relationships between groundwater discharge, alluvial storage and riparian vegetation in river systems with perennial to highly episodic flow;
  - development of methods to characterise the sensitivity of phreatic plants and vegetation to water table changes; and
  - the sensitivity of the regeneration of different riparian species to flooding regimes (flood levels, recession rates, scouring)

(viii) ***Identification of areas in SA where vegetation/groundwater interactions are critical to the water balance***

Studies in this area should aim to provide information or guidelines on the following aspects:

- Identification of the sensitivity of these areas to droughts.
- Identify conservation areas and priorities where the systems are particularly dependent on groundwater and studies to:
  - re-interpret existing vegetation maps to assess the vulnerability of different types to groundwater abstraction; and
  - understand hydrologic processes at these sites;
  - evaluate how drought affects these sites;
  - define the ecological requirements of these systems in terms of, *inter alia,* the quantity and variability of water supply.

Research priorities

In this section the workshop participants grouped and arranged the research issues described above in order to give a provisional list of priorities. Topics are arranged below roughly in perceived order of importance, and subdivisions are ranked as A, B or C to indicate priority.

1. *Book of Numbers*

This should have a high priority because better data and guidelines are required by people who are having to make decisions about groundwater utilisation and it potential impacts on a day to day basis.

2. *Mapping of hydrological response units (including groundwater)*

A national scale classification of hydrological landscape units which includes both groundwater and surface water resources is needed to plan and manage water resources effectively and to achieve the aim of sustainable utilisation.

3. *Groundwater-vegetation interactions*

A. Identification of sensitive vegetation - where is vegetation vulnerable as a result of the exploitation of groundwater

B. Identification of critical groundwater use zones - where is groundwater a primary resource that may need protection

4. *Analysis of case studies*

An analysis of the case studies collected in the report, and any others that may come to light to provide better answers to the following questions: What do we know about the process of vegetation - groundwater interactions in South Africa? What don't we know?

5. *Hillslope hydrology*

Research is needed to improve the present very sketchy understanding of hillslope hydrology in hydrologically in different landscape types found in South Africa.

6. *Effects of land-cover change*

The key topics for research relating to land use change are listed below in order of priority:

A. Afforestation effects on groundwater

A. The effects of land degradation related to rural settlements - emphasizing the effect degradation has on local groundwater recharge and thus on local water supply.

B. Management of veld, and its effects on groundwater.
A key form of veld management is bush clearing in savanna, or thicket, to plant crops or augment groundwater recharge; the effects of bush clearing on water quality should also be addressed.

B. The effects of the clearing of alien plants on groundwater and catchment hydrology.

B. Selection of species for woodlot planting that will minimise the impacts on groundwater and are environmentally acceptable.

C. Effects of sugar cultivation on groundwater.

C. Effects of maize cultivation on groundwater.

7. *Effects of groundwater exploitation*

These research projects should specifically address issues such as the impacts of rates of change in groundwater levels and changes in flooding regimes. The key topics for research are listed below in order of priority:

A. Effects on alluvial aquifers with phreatophyte communities, for example the Limpopo and other rivers with extensive alluvial beds.

A. Effects on coastal aquifers feeding lagoons, coastal marshes, and similar systems; a specific case is the groundwater-based irrigation on the Cape West Coast.

A. Effects on springs and base flows in Eastern seaboard regions (high and moderate rainfall regions), where groundwater frequently discharges at springs, or people are dependant on perennial streams.

A: Effects on dolomite system aquifers which discharge along the Mpumalanga and Northern Province escarpment (Wolkberg, and "Sabie" catchment).

B. Exploited dolomite aquifers elsewhere.

B. Mine de-watering and its effects on groundwater tables, wetlands (drying-up) and water quality issues.

C. Heavy exploitation of groundwater for irrigation (for example in the Tosca, Dendron and Coetsersdam areas in the Northern Province) - what are the effects on vegetation?

C. Are phreatophytes in bedrock river systems sensitive to groundwater manipulation?

C. Does groundwater exploitation in the karoo increase the risk of donga formation and erosion of the limited alluvial bank storage?

C. Are baobabs being affected by groundwater exploitation?

8. *Evaluation of the present groundwater monitoring programme*

The present groundwater monitoring programmes and recommended methodology, co-ordinated by the Department of Water Affairs and Forestry, does not address the groundwater-vegetation interactions. Although the information on this topic is limited, the present approach needs to be evaluated and adapted to incorporate our current understanding of the principles and the relative importance of the processes involved.