A review of information on interactions between vegetation and groundwater

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Abstract

Vegetation plays key roles in the interactions between groundwater and surface-water systems, because of its direct and indirect influence on recharge and because of the dependence of vegetation communities on groundwater. Despite this, groundwater and surface water have traditionally been treated as separate legal entities in South Africa and scientific disciplines have also tended to view them as separate, or at least separable, hydrological systems. This situation is beginning to change as South Africa's new Water Act recognises them both as inseparable elements of the hydrological cycle. The Act also requires that water resources be managed sustainably and a much greater understanding of these interactions is needed to meet this obligation. This paper provides a review of what is known about groundwater - vegetation interactions based on local and international literature and on information from the "grey" literature and unpublished sources. Changes in vegetation cover and structure, particularly from low vegetation such as grassland to tall vegetation such as a forest can have a significant impact on groundwater recharge by altering components of the hydrological cycle such as interception and transpiration. Recent research has shown that root systems often extend to more than the 1 m maximum used in defining agricultural soils and frequently to more than 10 m deep where the physical conditions permit root penetration. Woody plants have the deepest root systems and are capable of extracting large volumes of water from depths of 10 m or more. In South Africa the impacts of vegetation changes on baseflow or groundwater have been documented in both humid and sub-humid catchments but the greatest changes in groundwater levels have followed type conversions in semi-arid savanna and on the coastal plains of Zululand. Transpiration of water by plants accounts for about half of the largest changes in the water balance associated with vegetation type conversions. Many plant communities, particularly those of wetlands and riparian strips are highly susceptible to changes in the depth to the groundwater, both annual and seasonal. The rate of change (positive or negative) in water-table levels may be important but the data are not conclusive. Interactions between groundwater and vegetation appear to be generally more pervasive and important than was believed in the past. This will be an important area for future research in SA.

Definitions of key terms

Aquifer A saturated, permeable geologic unit that can transmit significant quantities of water under ordinary hydraulic gradients.

Ecological reserve A legal term; the quality and quantity of water required to protect the water resource for ecologically sustainable development and use of the relevant water resource.

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

Evapotranspiration In modern usage is replaced by the term evaporation, as defined above.

Groundwater Subsurface water in the saturated zone.

Phreatophytes Plants, typically riparian, that habitually obtain their water supply from the saturated zone. 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.

Riparian Growing alongside rivers or streams.

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_t but sometimes Et.

Water table The upper surface of the saturated zone where the water pressure is equivalent to atmospheric pressure (the upper surface of an unconfined aquifer).

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Introduction

This review was performed as part of a project undertaken by the CSIR under contract to the Water Research Commission (WRC), culminating in a report entitled *The Interaction between Vegetation and Groundwater: Research Priorities for South Africa* (Scott and Le Maitre, 1998). It concentrates on studies of the impacts of vegetation on groundwater recharge as well as those which assess the potential impacts of groundwater extraction on vegetation health, at the landscape to regional scale. Evidence has been gathered from the published literature and supplemented with information from 'grey' literature and unpublished records supplied by various sources.

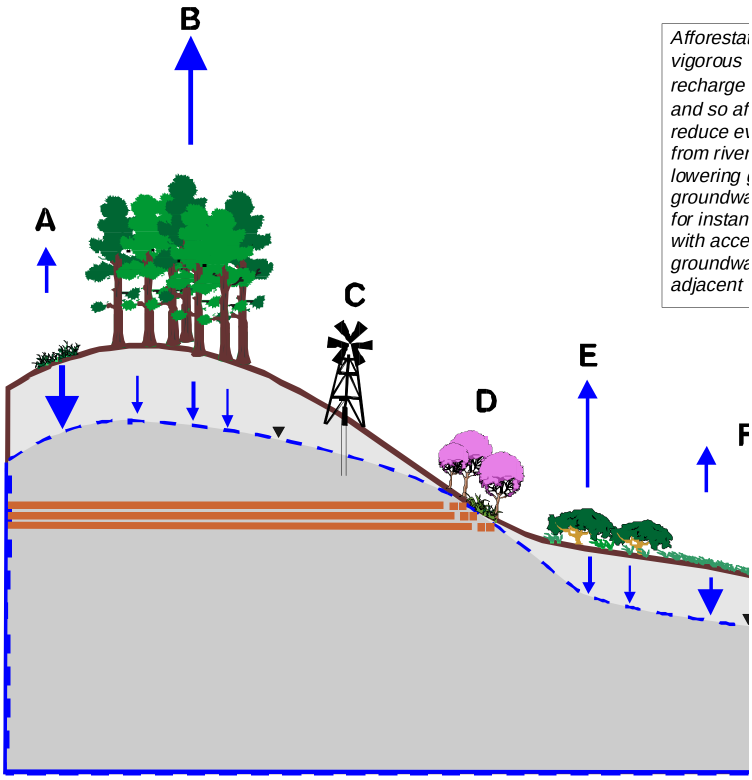

Figure 1
Schematic diagram illustrating some typical interactions between vegetation and groundwater

Vegetation-groundwater interactions are the focus of renewed interest. Concepts such as the ecological reserve and streamflow reduction activity as defined in the new National Water Act (Act 36 of 1998), demand that the interrelationships between vegetation and all water resources are understood and taken into account. The Environmental Clause (No. 24) in the constitution (Act 108 of 1996) requires all natural resources, including water, to be utilised on a sustainable basis. The principles of the National Water Act also give the environment and basic human needs priority over all other demands for water (DWAF, 1996). These requirements will place new demands on the managers of groundwater resources: they have to ensure that the necessary reserves are not being depleted and that utilisation does not lead to damage to the environment, including ecosystems which depend on groundwater. A greater understanding of the groundwater requirements of plants will be required to enable a determination of the ecological reserve before water-use licences may be granted or renewed.

A limited number of studies in South Africa have focused on the interactions between vegetation and groundwater. A larger body of literature is available on work carried out overseas in similar environments such as Australia and Spain. In South Africa, most of the work on the interaction of plants and soil or surface water has been carried out in the disciplines of soil science and surface-water hydrology. The traditional division of hydrological sciences into geohydrology and hydrology has kept the study of water use by plants in the domain of hydrologists. This division in the hydrological sciences was also embodied in South African law. The Water Act of 1956 and its predecessors did not recognise that surface- and groundwater were interrelated. This deficiency has been addressed in the water law review process and Principle A.1 declares that surface- and groundwater systems are indivisible (DWAF 1995; 1996). The growing interest in interactions between groundwater and vegetation, particularly in semi-arid areas, reflects the current trend towards a holistic approach and integrated management of natural resources.

Vegetation affects aquifers by directly extracting groundwater from saturated strata and reducing the proportion of rainfall that is eventually recharged by interfering with the passage of precipitation from the atmosphere to the water table in recharge areas. A recent review of techniques for modelling recharge in South Africa (Bredenkamp et al., 1995) points to the importance of incorporating evaporation losses in modelling recharge. Measurement and modelling of the recharge on the Atlantis and Zululand coastal aquifers have highlighted the impact of vegetation cover on recharge, and abstraction from shallow groundwater (Kelbe et al., 1995; Van der Voort, 1998). The effects of fluctuating piezometric surfaces on vegetation communities have been studied to a limited extent in South Africa and more widely overseas. Most work has been carried out in riparian zones, wetlands and areas of evaporative discharge. Alluvial aquifers have therefore received the most attention. There is little direct information available on vegetation-groundwater interactions on fractured aquifers, which occur across approximately 90% of the surface area of South Africa (Vegter, 1995). Information is also available indirectly from studies of stream and river baseflow in mountain catchments, many of which are groundwater fed.

The dynamics of plant decomposition and nutrient uptake may also influence the quality of water recharging the aquifer.

TABLE 1
INTERCEPTION LOSSES FOR DIFFERENT VEGETATION TYPES IN SOUTH AFRICA

Vegetation type	Type of estimate	Loss (units)	Source
Savanna	measured and modelled	15-20 % of gross rainfall	De Villiers and De Jager (1981) De Villiers (1982)
Burkea savanna Grassland	modelled	6 % of annual rainfall 18.5 % (likely to be half this or less)	Scholes and Walker (1993), Nylsvley
Protea shrubland fynbos	measured and modelled	6.1 %, rainfall 1500 mm	Versfeld (1988)
Indigenous forest Bushveld Fynbos Karoo Grassveld	modelled	3.1-3.5 mm/rainday 1.0-4.4 0.5-2.0 0.2-0.8 0.9-2.6	Schulze (1981)
Grassland	measured	12.7% weekly	Beard (1962)
Pinus radiata plantation	measured and modelled	rainfall 1 300 - 1 700 mm 10.3 % - 8 years old 12.2 % - 11 years old 20.0 % - 29 years old	Versfeld (1988), Pienaar (1964) Western Cape
Plantation: *Pinus patula* *Eucalyptus grandis*	measured and modelled	rainfall 1 700 mm 10% 5%	Dye (1996a), Mpumalanga
Wattle	measured	15-20%	Beard (1956)

This has been studied in detail world-wide in agricultural settings, particularly in terms of nitrate. However, little work has been carried out to examine these processes in natural ecosystems in South Africa and quality aspects are not covered in this review.

Impacts of vegetation on groundwater

This section has been arranged according to the sequence in which events typically occur in the movement of water from rainfall to groundwater. In summary, they are:

- Redirection of precipitation by the vegetation canopy; which water is then either evaporated or channelled to the ground via stemflow or which drips from the canopy or stem to the ground as part of throughfall.
- Stemflow is intercepted water that flows to the ground via the surface of the branches and stem.
- Litter on the ground surface tends to retain more water than bare soil and improves conditions for infiltration into the soil.
- Roots may provide channels for the preferential flow of water through the unsaturated zone to the water table, particularly in low-permeability soils, thereby increasing recharge.
- Extraction of soil water in the unsaturated zone by plant roots, to feed transpiration, decreases the amount of percolating water that reaches the saturated zone (recharge).
- Extraction of saturated zone water (groundwater) as evaporative discharge from the system that may depress the piezometric surface.

Interception

The term interception is used to describe the precipitation which is retained by, or absorbed into, the surface of the plant (bark, leaves) or litter and then evaporated directly back into the atmosphere. The most accurate estimates of interception have come from studies which have quantified the losses for individual rainfall events on time-scales of minutes to hours. In practice high-resolution data like these are rarely available and the measurements of estimates have been summarised as daily or annual losses. Vegetation changes (e.g. from grassland to plantation) can have a significant impact on the amounts intercepted and ultimately on groundwater recharge (Table 1).

The amounts that are lost depend on the duration and intensity of the rainfall and the area and roughness of the plants' surfaces or litter which retain or absorb the water (Larcher, 1983). High rainfall intensities and long-duration rainstorms (events), open plant canopies and smooth bark will all result in lower interception. Coniferous forests (e.g. pine, spruce) and plantations have dense canopies with high leaf areas and rough bark, and measured interception losses range from 15 to 24% (Farrington and Bartle, 1991; Calder 1992) but losses of nearly 60% (Lunt, 1934) have

TABLE 2
RELATIVE WATER INFILTRATION RATES IN RELATION TO SOIL TEXTURE AND PRESENCE OF A WOODY CANOPY, FROM STUDIES IN SEMI-ARID REGIONS IN AFRICA (AFTER BREMAN AND KESSLER, 1995)

Country and source	Soil texture	Canopy specifications	Relative infiltration rate (%)
Zimbabwe (Kennard and Walker, 1973)	Sandy	Closed canopy Open canopy Open grassland	100 84 55
Zimbabwe (Kelly and Walker, 1976)	Variable	Complete litter cover Partial litter cover No litter cover	100 33 12
Kenya (Belsky et al., 1989)	Loamy	Under canopy *A. tortilis* Open field Under canopy *Adansonia* Open field	100 25 100 20
Kenya (Scholte, 1989)	Loamy	Under shrub Open field	100 5

been recorded where rainfall intensities are low and conditions misty. Interception in natural eucalypt forests in Australia varied from 1 to 20%, increasing with increasing canopy cover and annual rainfall (Sharma et al., 1987b), while in acacia woodland it ranged from 5 to 13% on an annual basis (Langkamp et al., 1982; Slatyer 1961; Pressland, 1973) and was 25% in *Acacia mearnsii* stands (Calder, 1992). Studies in temperate forests have generally shown that the rapid evaporation of intercepted rainfall from tree canopies is an important loss, comprising 20 to 40% of gross rainfall in conifers and 10 to 20% in hardwoods (Zinke, 1967). This loss is substantially smaller in grasslands and heaths, and the difference is thought to account for much of the observed increase in evaporation following afforestation in temperate climates.

The estimated annual interception losses in *Pinus radiata* stands in the winter rainfall region ranged from 10% of the rainfall at eight years of age to 20% at 29 years of age (Pienaar, 1964; Versfeld 1988). The annual interception in a mature *Acacia mearnsii* stand in the Natal midlands was estimated at 15 to 20% of the gross rainfall (Beard, 1956). Two rainfall interception experiments were undertaken in the Sabie area of Mpumalanga, in a 4-year-old *E. grandis* and in a 9-year-old *P. patula* stand (Dye, 1993). For each rainfall event, the difference between gross rainfall measured above the canopy and throughfall and stemflow beneath the canopy was ascribed to canopy interception. These studies revealed that canopy interception loss amounted to 13% of gross rainfall in the *P. patula* stand (based on 125 rainfall events), and only 4.1% in the *E. grandis* stand (based on 56 rainfall events). These losses are much less than those reported in many temperate forests, but reflect the less frequent and more intense rainfall which is characteristic of most afforested regions in South Africa. Both these attributes ensure that interception loss in South African forest plantations is 20% or less of gross rainfall. The conclusion is that transpiration from dry canopies is the dominant evaporation process.

Stemflow

When the branch and stem surfaces reach saturation some of the intercepted water will flow down the stem to infiltrate the soil around the stem base. This stemflow averages about 5% of annual rainfall but can reach 22 to 40% in some cases (Slatyer, 1965; Pressland 1973; Navar and Ryan, 1990). Stemflow results in a high concentration of water because the wetted soil in the vicinity of the stem base can receive 15 to 18 times the annual rainfall (Specht, 1957; Navar and Ryan, 1990). The resultant spatial heterogeneity in soil-water fluxes will be significant in dry areas but less important in high rainfall areas where soils become more evenly wetted.

Infiltration and percolation

Infiltration is the process by which water moves through the soil surface into the soil matrix and percolation is the process by which it moves down through the profile and into the underlying weathered rock. Vegetation has a significant impact on infiltration both by providing canopy and litter cover to protect the soil surface from raindrop impacts and by producing organic matter which binds soil particles and increases its porosity (Table 2). Higher porosity increases infiltration and percolation rates and the water-holding capacity of the soil (Valentini et al., 1991; Dawson, 1993).

Infiltration rates are positively related to litter and grass basal cover, being up to 9 times faster with 100% litter cover than for bare soil (O'Connor, 1985). On red soils in the Matopos, Zimbabwe, infiltration in degraded veld was < 50 mm/h compared with 100 to 200 mm/h on veld in good condition (Macdonald, 1978).

One study found that replacement of deep-rooted eucalypt forest with shallow-rooted grassland reduced infiltration rates, decreased saturated hydraulic conductivity 10-fold and sorbtivity 3-fold (Sharma et al., 1987b). In another Australian study, a grassland catchment, cleared of eucalypt forest 80 years previously, generated high-peak stormflows and large discharge volumes regardless of antecedent moisture level (Burch et al., 1987). A similar, undisturbed (eucalypt) catchment nearby produced little runoff provided soil moisture levels were <60% of storage capacity, indicating greater deep drainage under the forest cover.

Use of grassland, such as grazing, may compact the soil, reducing infiltration. One 3-year study found that grazing did not alter the general patterns of seasonal soil-water recharge and depletion (Naeth et al., 1991), but grazing reduced soil water most in the wet season, and that the differences decreased towards the end of the dry season. The higher water use of the more abundant grasses appears to have been less than the increase in the amount of rainfall which infiltrated the soil and the decrease in soil evaporation. The higher infiltration rates in ungrazed grassland were related to lower bulk density, lower penetration resistance and a 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 infiltration rates were slightly lower under trees (Belsky et al., 1993).

Preferential flow via root channels

Plants also increase percolation rates by providing root channels to aid the flow of water through the profile. The benefits differ between different kinds of plants depending largely on the depth and coarseness of their root systems. This mechanism is known as preferential flow and also occurs where there are other forms of macropores, such as cracks, in the soil profile. Preferential flows can have a significant impact on recharge rates, increasing vertical water flux densities from 2.2 to 7.2 mm/yr to 50 to 100 mm/yr (Johnston, 1987a) and reducing the time for water to percolate to a depth of 6 m from 1 700 years (via soil matrix flow) to 30 years (Johnston, 1987b). Similar spatial heterogeneities in soil water flux have been reported from studies in Kenya (Nkotagu, 1996) and in Karoo soils (Van Tonder and Kirchner, 1990). The importance of preferential flow can vary with soil texture. In porous sands about 50% of recharge was via macropores compared with almost 100% in a lateritic profile (Sharma et al., 1987a).

In one study in Western Australia, root channels beneath eucalypt forest provided conduits for the penetration of rain water to a depth of 12 m over a period of 20 years, whilst rainwater on wheat lands in the same area had penetrated no deeper than 2.5 m (Allison and Hughes, 1983). Soils beneath eucalypts may be particularly water-repellent, thus inhibiting infiltration and channelling water to preferential flow paths (Burch et al., 1989; Scott, 1991). In addition, soils in South African eucalypt plantations have shown changes in physical and hydraulic properties that lead to enhanced deep drainage by means of macropores (Musto, 1994).

Soil water, groundwater extraction and root depths

Plants also decrease recharge by extracting water from the soil profile to transpire through their leaves. Transpiration ranges from as low as 5% of the annual rainfall to 100% (or more in situations where plants are tapping stored water) but generally ranges between 45 and 80% (Larcher, 1983). It therefore is the primary process of water loss where there is vegetation cover.

Depths of root systems and water extraction

Although some instances of deep roots are well known, the extent and importance of deep rooting by plants, and thus their ability to dry out soil profiles and the regolith to great depths or tap groundwater directly, are not generally appreciated. Many hydrological studies only examine processes in the upper 1.0 m or so of the soil profile based on the observation that most roots are located in the upper soil layers. Although 60 to 90% of the roots of woody shrubs and trees are located in the upper 0.5 m (Dobson and Moffat, 1995; Jackson et al., 1996), the remaining fraction of deep roots 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; Stone and Kalisz, 1991). In some shrub and tree species from the mediterranean-type climatic region of Western Australia the hydraulic conductivity of sinker roots is substantially higher than that of lateral roots, mainly due to the very long xylem vessels (1.5 to 2.0 m) in the former (Pate et al., 1995). Similar differences in root anatomy between the tap roots and other roots have been recorded in phreatophytes (Dawson and Pate 1996) and in a Cape *Protea* species (Higgins et al., 1987) and may be widespread in deep rooted species.

Recent reviews show that root depth is generally only limited by water tables or by soil or regolith characteristics that prevent rooting (Cannon, 1949; Stone and Kalisz, 1991; Nepstad et al., 1994; Stone and Comerford, 1994; Canadell et al., 1996; Jackson et al., 1996). 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). Even in 'wet' environments such as evergreen tropical forests, a number of tree species have deep root systems (> 8 m) which enable them to tap deeper sources and 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 (Stone and Kalisz, 1991). Many, but by no means all, savannah trees are deep rooted, with legumes such as *Acacia* and *Prosopis* reaching depths of 3 to 20 m and even >53 m in one case (Stone and Kalisz, 1991). *Eucalyptus* is another genus which has deep root systems, often reaching 10 m and 60 m in one case. Many shrub species have roots penetrating 3 to10 m or more where soil conditions permit (Hellmers et al., 1955; Specht and Rayson, 1957; Dodd et al., 1984).

Numerous species in arid and semi-arid environments have shallow, spreading root systems which are used primarily to scavenge water for storage in the plant; this group includes most succulents such as cacti, aloes and even baobabs, *Adansonia digitata* (Breman and Kessler, 1995; Caplan, 1995). Herbaceous annuals, desert ephemerals and succulents typically have shallow roots (<0.3 m) while herbaceous perennials usually have relatively shallow root systems (<1.5 m). In some herbaceous plants such as lucern (*Medicago*), the roots may reach depths of tens of metres (Stone and Kalisz, 1991; Stone and Comerford, 1994; Jackson et al., 1996).

Root depths in South Africa

Eucalypts in South African plantations may extract water from considerable depths. A study of soil water profiles on a site with a deeply weathered Nelspruit granite found that three-year-old *Eucalyptus grandis* trees were extracting water from depths down to 8 m, while 10-year-old trees, cut off from rainfall, abstracted water largely from below the maximum measured depth of 8 m (Dye, 1996b). This particular study shows that eucalypts had

TABLE 3 EVAPORATION FROM DIFFERENT SUCCESSIONAL STAGES OF CENTRAL FREE STATE GRASSLAND BASED ON A LYSIMETER STUDY AND SHOWING THE EFFECTS OF CARRYING OVER WATER STORED IN THE SOIL PROFILE FROM WET YEARS INTO DRY YEARS (SNYMAN, 1988)					
Period	**Rainfall (mm)**	**Evaporation (mm)**			
		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

established deep roots when still young even though the upper profile could have supplied the water they needed. The deep roots alone could maintain an adequate water supply to the trees.

Studies using stable isotopes of water indicated that plantation trees (eucalypts and pine) in Mpumalanga and Zululand were using groundwater during a drought period in 1992 (Midgley et al., 1994). Root excavation studies on the Zululand sand plain showed that both pine and eucalypt trees developed strong sinker roots to a shallow water table between 3 and 6 m below ground level (Haigh, 1966; Scott, 1993).

Soil-water dynamics

Soil-water replenishment and seasonal water contents were studied in three ecological sub-types of a *Burkea* tree savanna in deep sandy soils which had a field capacity of about 80 mm/m under a variable rainfall averaging 530 mm/yr (Moore et al., 1982). The soils in the sub-types characterised by *Eragrostis pallens* and *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 to 0.6 m layer. Under *Ochna* the profile was dried out to 0.6 m with no extraction below 0.9 m. The sub-type characterized by *Grewia flavescens* showed drying-out throughout the profile (1.4 m+), and slower wetting to lower maximum moisture levels after rainfall events. Recharge to deeper levels therefore seems unlikely in the *Grewia* sub-type. Modelling of this system suggested that at a similar site (Nylsvley) wetting fronts from rainfall rarely reach further than 1 m depth because the soil capacity is equivalent to the volume from typical rainfall events and sequences (Scholes and Walker, 1993). Evaporation is thus equivalent to rainfall, with about one third being lost via transpiration. Recharge to deeper levels (the water table is at 20 m) will happen only after exceptional rainfall.

Clearing of bush (trees and shrubs) in the Thabazimbi district (Northern Province) resulted in the water table (piezometric surface 40 to 80 m below the surface) rising by about 20 m over a 30-year period (Vegter, 1993). This was apparently due to increased recharge which occurred only during wetter years. 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 thought to be caused by abstraction by lowveld trees. In 1957 high rainfall over a short period recharged groundwater to 1943 levels. Clearing of low savanna and thicket to permit cultivation for pineapple production in the False Bay area (relic 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).

Percolation under grassland and crops was measured with lysimeters in the Pretoria area (O'Connor, 1985). Under fallow conditions there was leaching to >1.68 m every year of 22% of the annual rainfall; under crops (maize) 11% percolated past 1.22 m; under natural grassland 11% reached 0.61 m, 6% reached 0.91 and 4% reached 1.22 m. The volume was directly proportional to the rainfall with deep drainage being effectively zero under grassland in dry years. Similar results can be inferred from lysimeter results on central Free State grasslands; evaporation was lowest under fallow and positively related to the grassland's successional stage (Snyman 1988; Table 3). Mean annual rainfall was about 560 mm/yr. Net rainfall (rainfall minus interception losses) and thus deep percolation will also vary with grassland condition and rainfall. Similar variations in water penetration have been recorded between tree- and grass-covered areas in West African savanna (Table 2) and Karoo veld (Milton and Dean 1996).

A study of a wattle (*Acacia mearnsii*) plantation on a farm north of Pietermaritzburg (KwaZulu-Natal) found that recharge was reduced from the expected 10% of annual rainfall (900 mm) under grassland to nil at 5 to 8 years after planting, presumably because of increased transpiration by the wattles (Kok, 1976).

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). A comparison of the potential impact of existing and additional plantations on the coastal aquifer at St Lucia (Rawlins and Kelbe 1991; Kelbe et al., 1995) found that the existing 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 (Kienzle and Schulze, 1992). Simulations with ACRU of groundwater levels beneath a hypothetical 100 ha eucalypt plantation on the Zululand plain showed a sharp drawdown over a 10-year period, the depth of which was determined by the assumed maximum rooting depth of the trees.

Net impacts on recharge

As described above, changes in vegetation composition, cover or management can alter groundwater recharge by altering interception, infiltration, surface runoff, transpiration and the depth of the rooting systems. The response of the water table to changes in recharge depends on the directness and "length" of the pathway between surface and groundwater. The next section reviews studies of the net impacts of vegetation change on recharge at the catchment scale in South Africa, and studies from other countries.

Surface runoff at the catchment scale

Indirect evidence for altered recharge comes from catchment-based studies of the effects of afforestation and deforestation on streamflow. An international review found that a 10% change in cover in humid evergreen (e.g. eucalypt, pine) forests results in a 30 to 40 mm change in streamflow (Bosch and Hewlett, 1982). The corresponding changes for deciduous hardwood (poplar, oak) and scrub were ±25 mm and 10 mm respectively. Impacts on baseflow were not analysed but it is likely that in these small closed basins a similar change would occur in baseflow (and by implication, therefore, this would be the effect on groundwater recharge as well).

There is a large body of evidence from studies on the impacts of afforestation in South Africa that provides reliable estimates of the effects of a land-cover change on hydrology and also, indirectly, groundwater in hard-rock aquifers (Nänni, 1970; Bosch, 1980; Hewlett and Bosch, 1984; Van Wyk, 1987; Bosch and Smith, 1989; Scott and Smith, 1997). The afforested catchments are in high rainfall areas (>900 mm/yr), 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 markedly reduces groundwater discharge.

In South Africa, this impact of forests is thought to be predominantly due to increased transpiration (hence the high productivity of the tree crops) rather than increased interception losses (Scott and Lesch, 1997). 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 direct abstraction from groundwater. Afforestation of the whole of the grassed Mokobulaan-A research catchment, Mpumalanga Province, with *Eucalyptus 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 expected 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" (Nänni, 1971), but the shale substrate (Daspoort Shales of the Pretoria Group) is fractured and contains water reserves to 45 m below the surface without being saturated (Dye and Poulter, 1991). The roots of the eucalypts penetrated more than 10 m into this profile and most of the water was extracted at depths greater than 3 m (Dye, 1996b).

Net impacts on recharge: Western Australia

The most direct evidence linking vegetation change and recharge rates comes from the numerous studies in Western Australia and south-eastern Australia where clearing of natural woodland or forest has resulted in rising groundwater tables, and as a consequence, the extensive salinisation of soils (Williamson, 1990). 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 x 10^6 m^3 annually). Annual production losses were estimated to be A$214.6 m. (Dumsday et al., 1989). The areas typically have winter rainfall of 500 to 1 200 mm/yr and pan evaporation rates of 1 200 to 1 800 mm/yr. An important factor is the highly permeable soils which result in minimal or no surface runoff. Recharge in deep profiles (10 to 30 m or more deep) varies markedly between different vegetation types and with practices such as grazing (Table 4).

Clearing of native mallee (shrub/tree savanna) in the Murray River basin has dramatically increased recharge from <0.1 to 0.2 mm/yr to 3 and 30 mm/yr (Barnett, 1989). 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 and George, 1992). Water tables beneath eucalypt plantations (rainfall 462 mm, pan evaporation 1 503 mm) were 2 to 4 m lower than in adjacent pastures, with the drawdown caused by the trees extending 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 and Heuperman, 1994). On heavy soils (loam on low permeability clay) the drawdown was evident up to 10 m from the treeline.

Studies of the effects of reforestation in catchments in Western Australia (713 mm/yr; 80% in winter; pan evaporation 1 600 mm) found that it lowered water-table levels (Schofield and Bari, 1991; Bari and Schofield, 1992). Between 1980 and 1988 there was a net rise in the minimum and maximum groundwater levels under pastures of 1.8 m and 2.0 m, respectively. Reforestation resulted in a lowering, beginning 3 to 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 the maximum level 5.8 m (7.8 m relative). Similar results have been reported for other catchments (Table 4; Bell et al., 1990; Hookey, 1987; Salama et al., 1993a,b).

Where there is vegetation in semi-arid or arid areas, water movement out of the rooting zone can be delayed significantly by hydraulic gradients caused by the extraction of water by roots (Stephens 1994; Tyler and 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

TABLE 4
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.

Vegetation	Annual rainfall (mm)	Soil and water table depth (m)	Annual recharge (mm or % of rainfall)	Source
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 and Colville (1970a, b) (soil water)
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 water)
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 and Bartle (1991) (chloride method, water balance)
Replacement of natural eucalypt forest by grassland	409 mean (339-494)	Colluvium and laterite on deeply weathered granite	0.4-1.0 mm increased to 10-25 mm	Salama et al., (1993a,b) (chloride method, water balance)
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 and 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 and Craig (1989) in Greenwood (1992)
Eucalypt forest	1230	Loam on deeply weathered granodiorite	40-100 mm deep drainage	Talsma and Gardener (1986)
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 water and moisture flux model)

Spha = stems per hectare, a measure of tree or shrub density

TABLE 5
A COMPARISON OF THE IMPACTS OF DIFFERENT VEGETATION TYPES ON EVAPORATION, RUNOFF AND RECHARGE (AFTER CARLSON ET AL., 1990). THE RAINFALL VARIED FROM 529 TO 769 mm/yr DURING THE STUDY PERIOD (LONG-TERM RAINFALL 646 mm/yr).

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

under *Banksia* shrubs and the drainage volume and duration (e.g. 88 vs. 132 d) were reduced under pines (Farrington and Bartle, 1991). Drainage was also lower between trees than next to tree trunks, probably because of stemflow.

Net impacts on recharge: Other areas

Conversion of Brazilian cerrado (savanna) vegetation to *Eucalyptus grandis* and *Pinus caribaea* plantations altered 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, pines 450 mm and 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 could recharge groundwater (Nepstad et al., 1994).

On undisturbed sites in the arid mid-west USA, infiltration rates are high with no overland flow occurring; but where vegetation is degraded or absent, 40 to 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 is expected to increase groundwater recharge and runoff. Recharge can range from 10 to 50+% of the annual rainfall of 340 mm on bare sandy soils, but beneath exposed silt loams there was no recharge because in these soils the subsurface water does not drain below a depth where it cannot be raised 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 to 0.8 mm/d) resulting in no recharge. Under winter annual grasses the profile remained more moist and there was recharge through the coarse sandy soils.

In the Negev Desert, Israel, recharge on sand dunes with no perennial vegetation was about 70% of the annual rainfall of 100 to 210 mm. 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 annual vegetation, which cover about 40% of the total area, are unlikely to recharge groundwater.

In vegetation with a mixture of trees and grassland, water balance differs between open areas and tree clumps (Table 5). 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 and Dowhower, 1991). This was primarily due the higher productivity of the formerly under-canopy grassland when mesquite was removed. 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 and Rambal, 1988; 1993). Generally in Mediterranean shrub lands water yield (runoff and deep drainage) only occurs once rainfall exceeds 550 to 600 mm. Overall, evaporation from these open Mediterranean woodlands is intermediate between that of grasslands and deciduous forest in north-eastern North America (Valentini et al., 1991; Dawson, 1993).

Impacts of groundwater abstraction on vegetation

There have been a few studies on the effects of the artificial lowering of the water table on plants and vegetation communities in South Africa. These cases can be divided into two inter-related groups: riparian vegetation dependent on groundwater flowing into or out of the river system (influent or effluent respectively) and wetlands. The results of studies conducted on areas of evaporative discharge in other countries are presented, as there are no documented South African cases.

Vegetation may be wholly or partially dependent on groundwater. Even in riparian zones where sources of surface water are also available, the vegetation may have a high degree of groundwater dependency. The availability of groundwater may influence the type of plant growth (e.g. shrub or tree) as well as the species assemblage. Phreatophytes (plants that use groundwater) are sensitive to changes in the hydrogeological regime. This may be in the form of a water table declining at a rate faster than root growth or an alteration in the annual fluctuations of the water table. Groundwater abstraction by man or the regulation of effluent rivers may result in these changes.

Riparian systems

The relationship between riparian vegetation and groundwater is frequently complex. Plants may tap water stored in river banks or in alluvial aquifers; which may be dependent on periodic flooding for their recharge; or may tap groundwater that is discharging into the streams. Studies have indicated that riparian trees may be essentially independent of water in the stream channel (Dawson and Ehleringer, 1991), but in other cases, trees may switch between a separate, deeper, groundwater source and the stream water.

Plants which are riparian specialists (also called obligate phreatophytes) are species adapted to fluctuating water tables and their roots typically remain in, or in contact with, the saturated soil layers. These species are sensitive to sudden water stress such as a sudden lowering of the water table (Rood and Mahoney 1990; Mahoney and Rood 1991; 1992) or changes in the duration of floods which results in changes in the soil moisture balance and water tables (Smith et al., 1991).

Studies of seedlings of riparian poplar species have shown that rooting depth tracks water-table depth. Seedling survival was >90% with a rate of water table lowering of 1 or 20 mm/d, but was only 40% and <25% with reductions of 40 and 80 mm/d, 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 of the former (Mahoney and Rood, 1992). Similar findings have been reported in comparisons of sands, loams and peaty substrates (Schwinzer and Lancelle, 1983). Plants grown with deep water tables show slower growth and resource allocation to roots is increased (Schwinzer and Lancelle, 1983; Mahoney and Rood, 1992). *Prosopis velutina* provides clear evidence of this: its growth form ranges from a shrub where the groundwater table is deeper than about 15 m, to 12 m tall trees where water-table depths are <6 m (Stromberg et al., 1993). In Arizona, USA it was found that permanent lowering of the water table will cause a continual and quantifiable decline in height and structural complexity of *Prosopis*, mortality, and eventual replacement by desert scrub (Stromberg et al., 1996).

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). Riparian wetlands in South Africa are an important habitat but there is very little information on them and their dynamics (Rogers, 1995). The convergence of surface and groundwaters in floodplains and hyporhoeic zones is an important factor determining landscape morphologies and their biodiversity and productivity (Stanford and Ward, 1993). This is partly a consequence of groundwater carrying higher quantities of nutrients than surface waters, with the latter usually being better oxygenated. The upwelling creates patches of high productivity in the hyporhoeic zones and aquatic systems which support greater animal densities and diversity compared with non-upwelling situations. In many situations riparian plants are tapping interstitial rather than surficial flows. Groundwater extraction could have severe impacts on the nature of such differentiated systems.

Sudden changes in depth to water tables (e.g. through damming of rivers) may cause severe stress and partial or complete mortality in large trees (30+ years old for poplars) which cannot grow their root systems rapidly enough to maintain adequate water supplies to their extensive canopies. The losses of riparian trees (e.g. reduction in abundance and species) may show lags of years to decades before becoming evident because it may require exceptional droughts before trees pass stress thresholds and begin to die. 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* (Red River Gum) trees with permanent access to streamwater extracted about 50% of their water from groundwater; those beside an ephemeral stream 70%, and those to which surface water was available only during floods used only groundwater (Thorburn and Walker, 1994: Dawson and Ehleringer, 1991).

Similar patterns were recorded in another study: more than half the water samples taken from *Eucalyptus camaldulensis* and *E. largiflorens* trees on the Murray River floodplains showed they used only groundwater, and groundwater comprised 40 to 80% of the water in the remaining samples (Thorburn et al., 1993). In *E. largiflorens* trees, the depths from which water was extracted ranged from 0.2 to 4.0 m, and for *E. camaldulensis* from 0.1 to 3.2 m. Regulation of the river 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 at distances in excess of 22.5 to 37.5 m away from channels. Short-term flooding of channels comprising 15 to 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 groundwater which, in turn, is related to changes in land-use in the adjacent areas (Jolly et al., 1993).

During the period from 1979/80 to 1982/83 the ephemeral Kuiseb River in Namibia did not flood i.e. flows did not reach the delta, and the piezometric surface in the alluvial aquifer dropped by 3 m (Ward and Breen, 1983). A number of large *Faidherbia (Acacia) albida* trees (riparian fringe woodland) died and the growth and vitality of riverine vegetation declined. Localised stands of young *F. albida* (established in 1974 and 1976) did survive suggesting that the large dead trees had lost their ability to adjust to the lowering of the water table. *Acacia erioloba*, a non-riparian species, has not shown any signs of mortality, presumably because it is better able to track changing water tables. Total evaporation from well-developed river fringe woodland of *F. 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 and Walker, 1993). Transpiration was equivalent to about 658 mm/yr and evaporation from the sand to about 186 mm/yr. *Faidherbia albida* seedlings have root growth rates of 100 mm/week and, unlike the mature trees, are able apparently to keep pace with the falling water table. *Acacia erioloba* is much slower growing and may only establish in wet years, suggesting it is more vulnerable to rapid declines due to groundwater extraction by pumping. The normal volume in the aquifer is such that there is a buffer between floods; good floods may even supply sufficient water to last five years. Pumping of groundwater, especially in a season without floods, could lead to aquifer depletion and tree mortality. The woodlands may then establish a new “equilibrium” density or possibly even collapse completely.

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’ (hillock) communities. The riparian vegetation included *Acacia karoo, Euclea, Rhus, Carissa, Lycium* and other genera which are more typical of savanna but are able to persist by tapping the alluvial and groundwater stores. These trees, together with their understorey, provide a habitat for many animal and insect species. Extraction of groundwater from these riparian systems could have a severe impact on these communities given the high probability of extended droughts and limited recharge.

Wetlands

Wetlands have seasonally or perennially saturated soil profiles. The saturation may be caused by ponding of surface flows or flooding, but in other cases is caused by groundwater discharge. The primary causes of wetland destruction around the world are through surface drainage networks, designed to transform them into arable land, and contamination with chemicals (Llamas, 1991). There are surprisingly few reports where the loss of wetlands or wetland function has been attributed to exploitation of groundwater in arid or semi-arid regions. Though such a process is likely to be very protracted, it is nonetheless quite feasible. 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. Many wetlands in South Africa also have been abused and some are in a seriously degraded state (Cowan, 1995).

One well-documented case of a wetland being affected by groundwater abstraction is in Spain. Factors which influence the impacts on wetlands are (a) whether it is a recharge or discharge landscape segment, and (b) the type of connection with the aquifer (Bernaldez et al., 1993; De Vito et al., 1996). Drawdown of the water table generally transformed these 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 through the loss of wetland plant and animal communities occurred before the traditional indications (e.g. lowering of groundwater table) became evident (Suso and Llamas, 1993). The Tablas swamps are fed by groundwater and two rivers, one of which is sustained by surface runoff and the other by groundwater. Historical records show that the swamps were perennial except during the driest summers. Abstraction from the regional aquifer for irrigation changed groundwater levels and recharge, transforming large areas of the swamps into recharge areas. The wetlands shrank from 15 to 20 km² to 0.7 km² with a loss of the ecologically important and diverse 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 soils (Llamas, 1988).

The Doñana wetlands in southern Spain face the same fate. Here the worst affected area was identified as the ecotone (the ecological transition) between the marsh and the moving or stable dune sands. Water-table lowering between 1970 and 1987 ranged from 0.9 to 1.2 m/yr resulting in wetland habitat losses in different areas of 39 to 74% (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 terrestrial birds (e.g. bustards), water birds and vertebrates.

Wetlands are important areas in terms of biodiversity as they 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 and Bedding, 1994; Cowan, 1995; Pressey, 1986). Thus the indirect impacts of wetland degradation can be substantial and must be assessed before utilisation of the groundwater can be considered.

Areas of evaporative discharge

There are areas, especially in semi-arid regions, where groundwater does not discharge at surface but is tapped by phreatophytes and lost to the atmosphere by transpiration (Bernaldez et al., 1985). In parts of Spain 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 7^0C cooler and relative humidity 14% higher). They form islands of high biodiversity and provide key habitats. Even small changes in groundwater 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 water abstraction from the aquifer or changes in local hydrology due to trenching and deep road or railway cuttings. Such areas also exist in Southern Africa, on the alluvial aquifers in rivers through arid and semi-arid areas (e.g. the Limpopo and Kuiseb Rivers).

Conclusions

Interactions between vegetation and groundwater occur at two related stages in the water cycle: interference in the processes by which precipitation reaches the groundwater reservoir and extraction of groundwater either through deep roots or by being situated in groundwater discharge areas. Vegetation composition and cover largely determine the proportion of rainfall that reaches the soil and may also influence infiltration, percolation and deep drainage, and the available storage capacity of soil profiles. The effects of vegetation can be both positive and negative: vegetation intercepts rainfall and transpires water obtained from the rooted profile (including soil, regolith, saprolite and rock fractures), but can also facilitate infiltration (by improving soil condition and creating surface storage opportunities) and plant root systems can increase percolation rates by creating macropores.

All the available evidence shows clearly that changes in vegetation alter both recharge rates and water-table depths. A large body of evidence comes from particular situations in Western and south-eastern Australia which share the following features:

- highly permeable soil profiles, at least for the upper few metres, so that surface runoff is negligible;
- winter or bimodal rainfall; and
- deep-rooted forest vegetation which used a large proportion of the available water.

In areas characterised by these features changes of vegetation cover from woodland to grassland or short-lived crops resulted in increases in recharge rates of 1 to 2 orders of magnitude. The applicability of the Australian findings to Southern African situations needs to be assessed. The studies and observations in South Africa suggest that changes in vegetation have a similar impact on the potential recharge. In sandy areas with shallow unconfined aquifers, changes in vegetation cover have apparently altered recharge.

The size of the total vapour losses associated with a vegetation cover is dominated, in South Africa, by the transpiration component and, to a lesser degree, by interception. Clearing of bush or, conversely, bush encroachment and invasion by exotic woody species may have a significant impact on groundwater recharge and thus on groundwater resources. In the higher rainfall (eastern seaboard) regions of South Africa, baseflow in streams is a fairly direct indicator of shallow groundwater levels, and thus groundwater and surface water systems are inextricably intertwined. Groundwater exploitation in these high-rainfall regions with shallow aquifers in the deep weathered zone, can be expected to have immediate effects on spring discharge and surface water yields.

The generally held assumptions that root systems are shallow and that the important parts for ecosystem function are those in the first 0.5 m of soil, are clearly incorrect. 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). This has important implications for recharge as deep rooted plants are able to dry out soil profiles and weathered rock and also tap groundwater directly to considerable depths. Of the natural biomes of South Africa, it is probably within the savanna biome that the largest changes may be effected by changes in tree cover because of the ability of the trees to dry out the profile to great depths (>10m) or even tap water tables at depths of 30 m or more. Phreatophytic plants are not all equal: some are apparently highly adaptable, and hence not vulnerable to changes in the groundwater regime (e.g. *Acacia erioloba*), while others are vulnerable to small changes in groundwater levels (e.g. mature *Faidherbia albida*).

Within alluvial aquifers of Southern Africa, a direct response between abstraction and vegetation can be expected, as the link between the aquifer and associated vegetation is direct. The coastal aquifers have a relatively high recharge and short residence times. The potential for significant interactions with vegetation, both by altering recharge and by means of direct abstraction of groundwater by plants, appears to be high as has been shown for pine plantations on the Zululand coastal plain.

Lowering of the water table can have a significant impact on terrestrial, riparian, wetland and evaporative discharge area communities. Raising the water table can be as harmful as lowering it and so can alterations of the seasonal and annual 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 is related to the rate at which the water table falls, but it is risky to generalise from the little that is known. Environmental concerns may limit the development of large groundwater exploitation schemes because of our inability to satisfactorily predict "downstream" impacts. For environmental impact studies we need to develop an understanding of the sensitivity and dependence on groundwater of different ecosystems, before we can predict the effects of groundwater abstraction.

The ecological requirements of systems that depend on groundwater are poorly understood, yet this is an issue that we shall increasingly be called on to address in South Africa. Even surface-water systems seem likely to be more dependent on groundwater reserves than is widely appreciated. We believe that hydrologists need to actively seek ways of enhancing our understanding of the interactions between groundwater and vegetation with the aim of supporting the sustainable utilisation of South Africa's limited but vital groundwater resources.

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