THE POTENTIAL IMPACTS OF INTERCEPTION BELTS ON THE MANAGEMENT OF DRYLAND SALINITY

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Abstract

The extent and rate of increase of dryland salinity are serious problems, with many environmental, economic and social ramifications. For the Upper South East catchment of South Australia, an Environmental Impact Study in 1993 recommended the implementation of a revegetation program, with a high priority option the strategic use of interception belts of trees. For this work, it was hypothesised that interception belts would be useful land management tools for sustainable control of dryland salinity. The main aims were to establish if interception belts could control rising groundwater, where in the landscape they should be planted and what configuration they should take.

At a red gum salinity trial site, spatial and temporal transpiration patterns of *Eucalyptus camaldulensis* (Lake Albacutya provenance) were examined using the heat pulse velocity technique and the stable isotopes of water. Soil and groundwater conditions were monitored. Shorter term monitoring of intra and inter-provenance variability of transpiration was carried out. At a trial blue gum (*E. globulus*) plantation, edge effects due to increased wind advection on transpiration rates were investigated.

Red gum transpiration varied between 0.13 and 4.2 times rainfall in summer and autumn and was approximately equal to rainfall at other times. Significant differences in water use, normalised to sapwood area, were found among trees along the saline gradient. Trees utilised groundwater for approximately half the year. In the blue gum plantation, edge trees showed higher normalised water use compared to inner trees when canopy conductance exceeded critical values. Effects were not evident when water availability became limiting.

Optimal locations for interception belts are suggested where groundwater is accessible and strong groundwater gradients for lateral leaching of salt exist. Size of belts depends on recharge zone size and recharge depth. In the Upper South East catchment, between 10,000 and 20,000 ha of interception belts would be needed to eliminate recharge from the dunes. Use of existing GIS datasets would enable calculation of precise lengths of belts required and thus necessary widths.

It is concluded that interception belts will be useful tools in the management of dryland salinity. Further study should examine performance of interception belts in finer scale groundwater models as well as in existing regional or more complex ecosystem process models.
Declaration of Originality

I certify that this thesis does not contain or incorporate without my knowledge any material previously submitted for a degree or diploma in any university or other tertiary institution and, to the best of my knowledge and belief, it does not contain any material previously published or written by another person except where due reference is made in text.

I give consent to this copy of my thesis, when deposited in the University of Adelaide library, being available for loan and for photocopying.

Signed

Peter John Taylor

this twenty-fourth day of February 1999
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Publications associated with this work

Journal papers

Taylor PJ, Nuberg IK and Hatton TJ 1998 ‘Enhanced transpiration due to wind effects at the edge of a blue gum (Eucalyptus globulus) plantation’. (submitted Tree Physiology)

Taylor PJ, Nuberg IK and Hatton TJ 1998 ‘Transpiration patterns of Eucalyptus camaldulensis trees along a saline gradient’. (in prep.)


Taylor PJ, Nuberg IK and Hatton TJ 1998 ‘An alternative approach for estimating sap fluxes in tree stems from point measurements of sap velocities’. (submitted Tree Physiology)


Conference proceedings and poster abstracts


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Chapter 1 - Introduction

1 Introduction

The Role of Trees in the Management of Dryland Salinity

Aim of the project

Methods
The Role of Trees in the Management of Dryland Salinity

In Australia today the extent of dryland salinity and its rate of increase are serious problems, with many environmental, economic and social ramifications (Land and Water Resources Research and Development Corporation 1993). More than three quarters of a million hectares were assessed to be affected to some degree by 1990 and in the south west of Western Australia alone this was estimated to be increasing at a rate of 18,000 ha per year (Schofield and others 1991). Since then, estimates have been upgraded and it is now claimed that over 2m ha are affected with the prognosis for 2050 exceeding 3.7m ha (Robertson 1996). Ferdowsian and others (1996) predict that in Western Australia more than 6m ha (31.8%) of cleared land are potentially susceptible before a new equilibrium between groundwater recharge and discharge is reached.

Dryland salinity occurs as a direct consequence of wide scale clearance of deep rooted perennial vegetation and its replacement with shallow rooted annual crops and pastures. The original hydrological equilibrium is disturbed, groundwater recharge increases and salt stores become mobilised. Where saline water tables rise to within the root zone, soil water potential becomes more negative until plants are unable to lower their own potential sufficiently to take up water themselves. This unchecked increase in salinity generally results in plant mortality.

Clearly, redressing the problems brought about by salinity requires an understanding of the hydrological regime and appropriate management of the various components of the water balance, particularly evapotranspiration. This naturally provides a criterion for sustainable agriculture, the objectives of which are the maintenance of both the long term and the short term productivity of agricultural lands (Prinsley 1991). Agroforestry, the integration of trees with agriculture, has great potential for correctly managing the water balance and hence improving both sustainability and profitability of farming systems. Apart from being used to rehabilitate degraded land and protect productive land from the onset of salinity, agroforestry systems can also improve farm productivity through provision of windbreaks, timber products and other valuable products.
The impact of trees on the water balance is complex. The main effect is an increase in the amount of water transpired annually over that achieved by crops or pasture. In the case of trees that can utilise groundwater (phreatophytes) this can be a substantial component. In addition, water as rainfall may be lost from the system through increased evaporation from leaf surfaces (interception losses). However, due to the additional cover supplied by the tree canopies, soil and understorey evaporation is likely to decrease. As the water table drops, discharge of shallow groundwater, if present, by soil evaporation will also decrease. Transpiration itself is highly variable both between and within species particularly with respect to the salinity of the supply. Choice of species, configurations of agroforestry systems and position in the landscape can therefore contribute to some degree to the success or failure of dryland salinity management (Marcar 1992).

Finally, dryland salinity is almost invariably a regional or catchment problem in that it recognises no property boundaries. As such the management of dryland salinity must be addressed at the regional level even though the implementation of ameliorative measures may be undertaken at the farm level.

This is most likely to be the case in the Upper South East catchment of South Australia (see Figure 1-1) where more than 400 properties exist and more than 80% of the region is planted with pastures. This is an important agricultural region for sheep and cattle production but since the appearance of the first signs of salinity in the early 1980s it has seen the loss of productive land increase to its current rate of 4-12% per annum. At present 37% of the area is estimated to be affected by dryland salinity and a further 26% is at risk. An Environmental Impact Study was commissioned and led to the proposal of several key recommendations, including the implementation of a revegetation program (Upper South East Dryland Salinity & Flood Management Plan Steering Committee 1993). One of the higher priority options suggested in this program was the use of interception belts of trees (Bulman and others 1993). These are defined as long, narrow plantings of high water use species, strategically placed in the landscape e.g. above the break of slope or around the perimeter of discharge areas. Before such
schemes may be incorporated into regional policy however it is necessary to determine how effective interception belts are likely to be.

Figure 1-1: Location of the Upper South East region in South Australia

**Aim of the project**

It is hypothesised that interception belts will be useful land management tools in terms of regionally sustainable control of dryland salinity. The aims of this project therefore are to establish whether or not interception belts are a feasible option for controlling rising groundwater. First and foremost, can they be expected to
transpire sufficient volumes of water (including groundwater)? If so, under what soil salinity conditions would transpiration be maximised and where in the landscape would they best be situated.

Methods

To achieve the main aim outlined above, the objectives of this study will essentially be:

- to determine water use patterns of a species growing on sites representing different regimes of soil and groundwater salinity. This will provide information about the potential water use of trees across a spectrum of salinity regimes.

- using the Upper South East of South Australia as a case study, assess the likely impacts of the implementation of interception belts with the assistance of existing spatial data sets provided by various government studies.

To achieve these objectives first requires a review of literature. In Chapter 2 there is a detailed explanation of the important issues associated with dryland salinity and its amelioration. This will set the context for the current work. To predict how interception belts are likely to operate, it is necessary to accurately determine the transpiration component as an input to the water balance and to be able to differentiate the possible sources of this water. Chapter 3 sets out all the relevant literature pertaining to water use of trees, from the theory to the practice of water use measurement. It also reviews the literature concerning the use of the stable isotopes of water for identifying the sources of tree water and will highlight the appropriateness of this technique in combination with the heat pulse velocity technique. The ultimate purpose of this chapter was to determine the most appropriate methods for this study.

The review of literature leads into the experimental design that is set out in detail in Chapter 4. This is divided into a number of field-based transpiration and isotope studies. The first of these examines the seasonal effects of salinity on water use strategies of a transect of trees along a salinity gradient, using the heat
pulse velocity technique and a mass spectrometry technique involving the naturally occurring, stable isotopes of water. A subsequent study over a shorter time period examines the inter- and intra-provenance variability of tree water use along a salinity gradient, again using the heat pulse velocity technique. The final experiment, using the same technique, was included to investigate possible differences in the water use of trees at the edge of a plantation when compared to inner trees. This has implications for the design of interception belts in terms of belt width and planting density. The following three chapters (5-7) present the results and preliminary discussion of the experimentation; chapter 5 includes a critical examination of the suitability of existing methodologies for analysing transpiration data and their subsequent modification.

Chapter 8 is a general discussion that evaluates the potential impact of the work and evaluates the hypothesis set out in Chapter 1. Some recommendations and possible ramifications conclude the chapter. Using the Upper South East of South Australia as a case study, the implementation of interception belts into a saline catchment is covered in Chapter 9. Note that, although the case study refers specifically to the Upper South East, the field experiments were carried out at Minlaton and Talinga, both of these sites being located outside of this catchment (see Figure 1-1). This eventuated because of the lack of suitable sites in the catchment but was still considered appropriate due to the generalised nature of the research and the intention that the findings be transferable between regions.
Chapter 2 - Issues associated with dryland salinity

2 The Development Of Dryland Salinity And Its Amelioration Using Trees

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Introduction

Salt is a naturally occurring phenomenon on land since it is constantly being recycled through rainfall, run off and streamflow. If undisturbed over time, equilibrium is reached between the amount of salt residing in the soil and that being returned to the oceans such that, in many parts of the world, areas of saline soils now occur naturally. This is known as primary salinity. Depending on the severity of salinity, the survival of all vegetation may be excluded (as in the case of dry salt lakes) or it may be merely limited to a range of salt-tolerant species (e.g. halophytes).

Dryland and irrigated salinity occur following man-induced disruptions to the naturally existing hydrological equilibrium, and collectively are known as secondary salinity. These two forms of secondary salinity are considered separately simply to differentiate between their mechanisms of disruption to the hydrological equilibrium. Irrigated salinity occurs generally because extra water is added to the system, whereas dryland salinity occurs generally because less water is removed from the system. The remainder of this chapter presents an overview of dryland salinity, its distribution, the process of salinisation and how trees may be of assistance in reversing some of the associated problems. It concludes with a summary of the important principles and areas of research required.

The extent of dryland salinity

Dryland salinity occurs to some degree on all continents bar Antarctica (Ghassemi and others 1995). In Australia, affected areas have been reported in all states except the Northern Territory (Robertson 1996) and in most states, the areas of land affected are on the increase (Schofield 1991). This is particularly the case in Western Australia, where it has been predicted that the area of cleared land currently affected by dryland salinity (about 9.4%) may double in the next 15-25 years and even double again before an equilibrium point is reached sometime in the future (Ferdowsian and others 1996).
Why salinity is a problem

Problems caused by salinity are generally economic, in that agricultural productivity is often reduced and water resources are degraded, but they can also be environmental, as in the case of wetlands and other natural systems whose viability can become threatened (Schofield 1991). In the Upper South East of South Australia for instance, long term losses in productivity, due to the reduced stock carrying capacity of land predicted to become saline, are estimated at 45% (Webb 1994). Within this catchment there are also areas of significant international conservation value, which are now under threat from rising saline water tables. In the Liverpool Plains area of New South Wales estimates of losses due to salinity are currently around $A11m per annum and in Victoria, estimates of losses in the Loddon and Campaspe catchments exceed $A4m per annum. The rapid expansion of dryland salinity and its associated costs has prompted the current demand for research into determining the best means for reversing or at least halting the problem.

How the salinisation process occurs

When deep-rooted perennial native vegetation is removed and replaced by shallow rooted annual crops, the hydrological balance becomes disturbed (Greenwood 1988). More water passes through the root zone than can be utilised by the plants and eventually some of this may reach the groundwater (Marshall and Holmes 1979). Significant recharge of the groundwater can then lead to a rise in the level of the water table with an associated mobilisation of salts that were previously stored in the unsaturated soil. Figure 2-1 illustrates this process.

Unchecked, this rising water table may reach the root zone, at which stage, plants begin to exhibit symptoms of stress due to osmotic effects. Further rises in water tables may lead to waterlogging and the appearance of saline seepage areas in the landscape (e.g. Greenwood and others 1992; Upper South East Dryland Salinity & Flood Management Plan Steering Committee 1993).
Ruprecht and Schofield (1991a) presented direct evidence of the link between the clearing of deep-rooted perennial vegetation and the subsequent occurrence of saline seepage in a 344ha catchment in the south west of Western Australia. Dramatic increases in groundwater levels and salinity were recorded and even after 13 years the system had not reached a new equilibrium. Lesser effects were shown by the same authors for a range of partial deforestation regimes in an adjacent catchment (Ruprecht and Schofield 1991b).

**Important principles for reversing or halting the process**

If the clearing of native vegetation is responsible for upsetting the hydrological equilibrium and setting in train the salinisation process, it seems logical that revegetating the landscape will reverse the problem. In reality however, this is seldom the case. Because of the mobilisation and relocation of salt at or closer to the soil surface, replanting of vegetation in groundwater discharge zones is unlikely to be successful. Reversal of the salinisation process requires the leaching of salt away from the root zone as well as the lowering of the water table (Leuning and others 1991). Prevention of excess water recharging the groundwater is a first
priority before the long and slow process of leaching surface salts can be achieved. Until the groundwater level is reduced beyond a critical level, discharge of groundwater directly by evaporation from the soil will continue, leaving salt deposits behind at the surface (Williamson 1986). This critical level, however, varies according to many soil physical, climatic and vegetation factors and so cannot be assumed to be a unique value for all soils. As an example, Jolly and others (1993) showed that, for four floodplain soils, the critical depth of groundwater, below which salt accumulation was prevented, increased with increasing clay content of the soil. Without a reduction in groundwater level, leaching of salts beyond the root zone will not be possible and the further addition of water in this situation will only contribute to raising or maintaining the existing water table level. In addition, the leaching process is likely to be slow in areas of low rainfall since the movement of salt beyond the root zone on a large scale is only possible by rainfall.

The use of trees in saline environments

Planting trees to control dryland salinity is one of the most favoured options and has recently been extensively reviewed by Farrington and Salama (1996). The most obvious role for trees in salinity control is in recharge prevention (Morris and Thomson 1983; Clifton and others 1993). Transpiring large volumes of water that would otherwise have passed through the root zone to the groundwater is potentially a significant means of correcting the disturbed hydrological equilibrium. Numerous studies, particularly in Western Australia, have shown how reforestation or agroforestry have been successful in lowering groundwater tables (e.g. Bell and others 1990; Schofield 1990; Schofield and Bari 1991; Bari and Schofield 1991; Bari and Schofield 1992; Greenwood and others 1994; Greenwood and others 1995).

The effectiveness of recharge control in isolation however may be limited if the trees become stressed due to a lack of available soil water in late summer and autumn, a period when atmospheric demand and consequently the potential for the trees to transpire at peak rates is normally very high. Similarly, the effectiveness may be limited in winter when evaporative demand is likely to be low. If the trees
are unable to utilise all the available water, excessive recharge may still occur. To overcome this, planting the trees lower in the landscape where they may be able to access the groundwater either directly or indirectly is potentially more efficient, particularly if the resultant mixture of waters does not have a deleterious effect on the ability of the trees to transpire (Greenwood 1986). (Note though that the potential for greater discharge is conditional on local hydrogeology facilitating adequate water supply rates to the tree roots). Eastham and others (1993a), in an evaluation of agroforestry species for salinity control, found that river red gums transpired in excess of rainfall in three successive years. A study by Greenwood and others (1985) comparing evaporation rates from 7 year old eucalypt plantations with pastures planted above a saline seep, showed that some species were able to transpire as much as four times the annual rainfall amount whereas the proportion of rainfall used by pasture was only 0.6. In contrast, the inability of a mixed eucalypt plantation to reclaim a saline seep at another catchment in Western Australia was partly attributed to the trees not being able to access the groundwater (Greenwood and others 1994). Where trees can access the groundwater, extraction of water from the soil can continue throughout the drier parts of the year, effectively creating a buffer zone in which excess winter rainfall may be temporarily stored. Strategically siting trees in this fashion therefore has two benefits over recharge control alone in that it allows continual peak extraction of soil water through periods of high atmospheric demand and guards against excessive groundwater recharge during periods of low atmospheric demand.

Some limitations on the use of trees in saline environments

There are obviously some limitations to transpiration rates, the most likely being due to the low water potential of the soil. For transpiration to continue at peak rates, the trees must be able to lower their own water potential below that of the soil. If this becomes increasingly difficult, as it may in very dry or highly saline soil, transpiration rates will be reduced. As discussed in the previous section, if the trees can access a source of water all year round, drought conditions in the root zone will be avoided, but only if the osmotic potential due to the salinity of that source has minimal effect on the trees' ability to transpire.
The effects of salinity on woody plants, as reviewed by Kozlowski (1997), are many but generally involve reduced vegetative and reproductive growth, morphological changes (or adaptations) and various physico-chemical alterations to cell processes. Munns (1993) suggested that growth responses to salinity were due firstly to a water stress effect caused by a decrease in soil water potential and secondly, to salt induced injury following a rapid increase in salt accumulation. The initial response therefore is to salt located outside the plant itself. This necessitates some degree of osmotic adjustment by the plant in the form of the internal synthesis of solutes, which in turn has associated physiological costs that result in a decrease in plant growth. Salt accumulation within the plant results in increased leaf senescence and mortality rates, which may further result in a reduced supply of assimilates and reduced growth.

Plants that can survive in saline environments do so because they have some mechanism for avoiding salt accumulation. Whether this is by salt exclusion, extrusion or dilution, these plants have a competitive advantage over salt sensitive species. Much research into growth and survival has been carried out to select suitable species and/or provenances for the amelioration of saline lands, both in the field and on seedlings in glasshouses (e.g. Biddiscombe and others 1985; van der Moezel and others 1988; Craig and others 1990; van der Moezel and others 1991; Marcar 1993; Eastham and others 1993b; Bell and others 1994; Greenwood and others 1994; Sun and Dickinson 1995, 1997). Studies into the water usage of trees specifically for selection for salinity control are rarer. Greenwood and others (1994) and Eastham and others (1994) both assessed water use indirectly, the former on the basis of survival ranking and canopy size and the latter by the soil water balance technique. In glasshouse trials van der Moezel and others (1989) examined the effects of waterlogging and salinity on stomatal conductance, net photosynthesis and transpiration of three month old seedlings of two eucalypt species which had the potential for planting in saline environments.

One of the most commonly studied species for use in salinity management has been the river red gum (*Eucalyptus camaldulensis*) and in fact this species featured in all of the above studies. A number of researchers have investigated the responses of clones of this species to waterlogging and salinity. Direct
measurement of clonal tree water use by the heat pulse velocity technique has been reported by Marshall and Bell (1991) and Marshall and others (1997) and other researchers (e.g. Akilan and others 1997a, 1997b; Farrell and others 1996) have shown that different provenances of red gum respond differently according to the salinity of the source water and the degree of waterlogging. The success or failure of the reclamation of saline land will undoubtedly depend on the ability of the trees not merely to survive but to grow and transpire at peak rates. Extending the potential zones in which trees can be planted, by using highly salt tolerant clones, will also be of benefit, particularly in agricultural environments where the loss of productive land to trees is often viewed as an unattractive option.

To make the planting of trees a more attractive option, fast growing eucalypts for pulpwood production have often been proposed for higher rainfall zones. In saline areas however, the more popular pulpwood species such as *E. globulus* perform poorly. Bennett and George (1996) suggested their replacement with river red gum which are better suited to the conditions. Extending this further in an attempt to combine the desirable growth and pulpwood characteristics of *E. globulus* with the salinity tolerance of *E. camaldulensis*, Oddie and McComb (1996) developed crosses between the two species with the intention of establishing field trials to evaluate their potential.

**Conclusions and important areas to be researched**

The effectiveness of trees for redressing the problems associated with dryland salinity depends on a number of physical and physiological factors, such as the depth and salinity of the groundwater, the ability of the soil to deliver water to the roots, the ability of the trees to access sufficient sources of water all year round and to transpire at sufficiently high rates. The key requirement of interception belts in particular is to remove as much water as possible but at the same time to occupy as small an area as possible.

To predict how effective interception belts are likely to be requires knowledge of transpiration patterns over a range of salinity regimes and seasonal climatic conditions. This will ultimately help determine the most suitable sites for planting
interception belts and indicate how their ability to extract water may respond seasonally to changing atmospheric demand.

The usefulness of such knowledge can be further enhanced if the variability of these transpiration patterns can be quantified both within and between provenances. Greater precision can be expected in the predicted removal rates and a clearer understanding of optimal planting sites may be gained if species or provenances can be matched to particular sites.

In the simplest one dimensional case, the rate at which water tables will be lowered is dependent on the ability of the trees to remove water at a rate in excess of precipitation i.e. to transpire groundwater as well as rain derived soil water. Trees that are unable to access the groundwater must rely solely on rainfall to survive. Consequently they may become stressed in times of drought resulting in reduced transpiration rates until the soil moisture is replenished. In contrast, trees that can access groundwater (phreatophytes) and are able to switch rapidly between sources are likely to transpire at rates closer to the equilibrium rate for longer periods. Quantifying the water balance for a specific site therefore requires a means of differentiating between these two sources of water.

In summary, determining the effectiveness of interception belts for controlling water tables in saline environments requires a detailed understanding of the ability of trees to remove large volumes of water as well as the physical and physiological limitations which affect that ability. The following chapter therefore reviews the available literature concerning the theory and measurement of evapotranspiration in order to identify important parameters and to select appropriate methods for this study. It follows with a review of a technique that uses the stable isotopes of water for differentiating between different sources of water being transpired.
# 3 Transpiration Theory and Measurement

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Chapter 3 - Tree water use and its measurement

Introduction

Paramount to investigating the effects of salinity on tree water use (and vice versa) is an understanding of the physical and physiological processes associated with transpiration and an ability to detect and measure transpirational fluxes within individual trees. In addition, to be able to partition these fluxes into rain-derived soil-water and/or groundwater requires a convenient method for differentiating between the available sources of water. The aim of this chapter is to identify from the literature important parameters that are required for determining patterns of tree water use in interception belts and appropriate methods for measuring them. A summary of the theories pertaining to tree water use is followed by a detailed description of the many influencing factors, their interactions and their relative importance. The remainder of the chapter is then devoted to reviewing the measurement and source differentiation of tree water use, thus facilitating the selection of suitable methodologies for this study. The chapter concludes with a brief summary.

Transpiration defined

Evapotranspiration is that component of the water balance which enters the atmosphere as water vapour, either by direct evaporation of intercepted rainfall from the surfaces of the vegetation and soil or by transpiration through plant stomata. The evaporation and transpiration processes are identical in terms of pure physics: in both cases liquid water is converted to water vapour with a continuous supply of energy supplying the latent heat of vaporisation (McIlroy 1984).

The evaporation process is driven purely by climatic factors such as solar radiation, humidity and wind, although it is influenced by physical aspects of plant canopies and rooting depths. The size and extent of plant canopies influence not only the amount of rainfall that is intercepted aboveground and then evaporated but also, through shading effects, the amount of water that is evaporated directly from the soil surface. Plants with extensive canopies, such as trees, can at times intercept more rainfall than agricultural crops and pastures for instance. Perennial crops and trees will shade the ground for a longer period than annual winter crops, particularly during summer, and plants with deeper rooting
depth, such as trees, will lower surface evaporation through removal of available surface soil water.

The relative importance of these effects at the catchment scale for instance, will be reflected in the relative areas of trees and agricultural land. When considering interception belts, the net increase of direct evaporation of intercepted rainfall from leaves and stems will obviously be minor with respect to the net increase in transpirational potential. Similarly, changes in soil evaporation rates under interception belts due to localised shading are also likely to be minor relative to the overall soil evaporation rate of the agricultural land they are protecting.

The major impact of interception belts on the water balance will be through transpiration and, because plants have the ability to control the rate of transpiration to a certain degree through stomatal feedback mechanisms, it is this process of transpiration that is the main focus of the following review.

**Factors influencing transpiration**

Transpiration is determined by a combination of factors that may be classified as atmospheric, edaphic or vegetative. Evaporative demand of the atmosphere varies according to solar radiation, air temperature, relative humidity and wind. Soil water potential determines the pressure differential that the plant must overcome to take up water from the root zone. This in turn varies according to soil moisture content, salt concentrations, hydraulic conductivity and soil texture. Within the plant itself, resistance to water flow must be overcome in the roots, the stem and the leaves. These resistances vary with different plant species and at different locations within plants (Grace 1983). In addition, aspects of the physical structure of plants and plant communities, such as height, roughness and density of planting, determine the degree to which transpiration is influenced by local air turbulence.

These many factors, influencing the rate of transpiration from vegetated surfaces, can be conveniently lumped into two terms, a radiative or energy driven component and an advective or diffusion driven component. These are combined
in the Penman-Monteith equation and describe transpiration (E) under steady state conditions as follows;

\[
E = \frac{s\Phi_n + \lambda\gamma g_a \Delta\rho_{va}}{\lambda\left[s + \gamma\left(1 + \frac{g_a}{g_c}\right)\right]}
\]

Equation 3-1

where

\(\Phi_n\) = net radiation, the available energy

\(\Delta\rho_{va}\) = vapour density difference between the vegetation (evaporating surface) and the air at some reference point.

\(g_a\) = the aerodynamic or boundary layer conductance between the vegetation surface (either leaf surface or effective surface in the case of “big leaf” models) and the bulk air stream

\(g_c\) = the conductance of water vapour between the substomatal evaporating sites to the vegetation surface (stomatal conductance in the case of leaves, or crown conductance in the case of individual trees or canopy conductance in the case of tree stands).

\(\lambda\) = the latent heat of vaporisation of water

\(\gamma\) = psychrometric parameter

\(s\) = the rate of change of saturated vapour density with temperature

These last three terms are all physical parameters that are temperature dependent.
Alternatively, the vapour pressure difference rather than the vapour density difference between the vegetation and the air is used such that Equation 3-1 becomes Equation 3-2 as follows;

\[
E = \frac{s\Phi_n + C_p \cdot \rho \cdot g_a \Delta p_{va}}{\lambda \left[ s + \gamma \left( 1 + \frac{g_a}{g_c} \right) \right]}
\]

Equation 3-2

where

\( \Delta p_{va} \) = vapour pressure difference between the vegetation and air

\( C_p \) = specific heat capacity of water

\( \rho \) = the density of air

The term "\( s \)" now becomes the rate of change of the saturated vapour pressure with temperature and the units of the psychrometric parameter (\( \gamma \)) change to reflect the change from density to pressure. All other terms are defined as before. Both forms of the Penman-Monteith equation are equally valid (Thornley and Johnson 1990).

**The concept of potential evaporation**

For \( E \) to reach an upper limit, the ratio of the aerodynamic conductance to the surface conductance must be a minimum. In the case of low, dense crops, which are wet, this ratio can approach zero and the Penman-Monteith equation reduces to the following expression (Equation 3-3) describing potential evaporation (PE);

\[
PE = \frac{s\Phi_n + \lambda g_a \Delta \rho_{va}}{\lambda \left[ s + \gamma \right]}
\]

Equation 3-3
Often for convenience of calculation, the advective term is assumed to be a proportion of the radiative term and the expression for PE reduces to the Priestley-Taylor equation (Equation 3-4) thus;

\[ PE = \alpha \frac{s \Phi_s}{\lambda (s + \gamma)} \]

Equation 3-4

where \( \alpha \) = the Priestley-Taylor coefficient, which, for most agricultural crops is taken to be around 1.26.

However, for tall, rough crops, such as forests, the assumption that the ratio of conductances approaches zero is not necessarily valid (Thornley and Johnson 1990) so potential evaporation from these systems is better estimated from the full Penman-Monteith equation using estimates of the minimum aerodynamic and maximum surface conductances.

**Aerodynamic (or boundary layer) conductance**

The conductance of water vapour between the leaves and the bulk air stream \( (g_a) \) is generally shown (for conditions of pure turbulence under neutral atmospheric stability) as a logarithmic function of wind speed, vegetation height and parameters which account for surface roughness characteristics of the canopy (Thornley and Johnson 1990).

\[ g_a = \frac{\kappa^2 u_a}{\ln \left( \frac{Z + \zeta_v - d}{\zeta_v} \right) \ln \left( \frac{Z + \zeta_m - d}{\zeta_m} \right)} \]

Equation 3-5

where

\[ \kappa = \text{von Karman’s constant} = 0.4 \]
\( u_0 \) = wind velocity at the reference height \( Z \)

d = the zero plane displacement or apparent sink for momentum, at which height wind speed \( u = 0 \) (assumed to be about 0.64h, where h= the vegetation height)

\( \zeta \) = the roughness parameter for heat and vapour exchange (assumed to be about 0.026h) and

\( \zeta_m \) = the roughness parameter for momentum exchange (assumed to be about 0.13h)

Sometimes the roughness parameters for momentum and for heat and vapour exchange are assumed to be the same and equal to approximately 0.1h (Grace 1983). In a mature *Eucalyptus globulus* plantation in Portugal, David and others (1997) for example, determined aerodynamic conductance assuming equal roughness parameters for vapour and momentum flow (0.13h) and taking the zero plane displacement to be 0.64h. It has been shown though that wind speed itself and tree spacing can influence the zero plane displacement (d) and roughness parameters. Vogt and Jaeger (1990) reported a decrease in \( d \) and an increase in roughness length with increasing wind speed in a pine forest, while Green and others (1995a) showed that, in a Sitka spruce plantation, \( d \) dropped from 0.75h at a 4 m spacing to 0.61h at 8 m.

For windbreaks and other “thin” plantations or isolated trees, where equilibration between the canopy and the turbulent boundary layer cannot occur, the assumption of a logarithmic wind profile is not valid. Aerodynamic conductance must be measured by other means, such as the heated leaf replica e.g. Brenner and Jarvis (1995); Domingo and others (1996) or the “hanging tree” method or a combination of both as described by Smith and others (1997).

Typically, aerodynamic conductances over tall, rough vegetation such as forests are much higher than those over short vegetation for a given wind speed (Grace 1983). Kelliher and others (1993) for instance, reported conductances for forests of around 200 mm/s, which were an order of magnitude greater than for grassland.
Surface (stomatal, crown, canopy and bulk vegetation) conductance

The surface conductance term \( g_s \) is a measure of the degree to which water vapour is able to pass freely from the evaporating sites to the bulk airstream. The terminology varies, depending upon the scale at which transpiration is being considered. For individual leaves it is termed stomatal conductance and is a measure of the ability of water vapour to move from the substomatal cavities through the stomata to the leaf surface. With individual trees, where all the leaves in the canopy are assumed to act as a single “big leaf”, it is often termed either crown or canopy conductance and includes not only the stomatal conductance component but also an aerodynamic component from the leaf surfaces to an “effective crown or canopy surface”. An extension of this, for studies of transpiration of stands of trees, is the term canopy or bulk vegetation conductance, which again includes a component of stomatal conductance and an aerodynamic component synonymous with the “effective surface” of the canopy of the stand.

Average maximum values of stomatal conductance for natural vegetation types are around 6 mm/s while values of bulk surface conductance, which includes components of plant canopy and soil, are typically around 20 mm/s (Kelliher and others 1995). The ratio of bulk vegetation to stomatal conductance is consistently close to 3 for a range of vegetation types (e.g. temperate grasslands, forests and agricultural crops) (Kelliher and others 1995; Schulze and others 1995).

Determination of surface conductance

Stomatal conductance of individual leaves can be determined by porometry, but because of very large within-tree variation, characterising whole canopies by this technique can be problematic as far as sampling is concerned (Jarvis and others 1981). Accuracy of the technique was reported to decline at high transpiration rates in a study on honey mesquite by Ansley and others (1994). For whole canopies of isolated or stands of trees, canopy or crown conductance can be determined by inverting the Penman-Monteith equation and substituting values of evaporation or transpiration measured by alternate techniques for \( E \) e.g. Granier and Loustau (1994); Kelliher and others (1995); Martin and others (1997). Consideration must be given however to the fact that there will be a time lag
between the response of the crown to atmospheric conditions and the associated response in sap flow measured in the stem.

Factors influencing stomatal conductance

Stomatal conductance can be considered as an indicator of the degree to which stomata are open and has been shown to be influenced by numerous factors. These include light, leaf temperature, vapour pressure deficit or humidity, assimilation rate, internal concentration of CO₂ and water stress (Grace 1983; Lynn and Carlson 1990; Leuning and others 1995). In most plants stomata open quickly under conditions of low, short-wave irradiance and continue to open more slowly as irradiance increases, tending towards a maximum conductance in what is described as a rectangular hyperbola response (Kelliher and others 1993). Porometer measurements on three pine species, for instance, indicated that stomata were at least 2/3 open by 1/3 maximum light conditions although this varied among species. In studies on Phaseolus vulgaris, Barradas and others (1994) showed that artificially changing the radiation produced a sigmoidal response in stomatal conductance although the rate of closure was faster than the rate of opening. Under water deficit, both the opening and closing rates were faster than for well watered conditions.

Leaf temperature influences stomatal conductance through its effect on the saturation vapour density of the air and other physical parameters, resulting in an optimum operating range of temperatures. The response of stomatal conductance to an increase in the leaf internal CO₂ concentration is negative but non-linear, possibly sigmoidal, though this does not vary much in the field (Grace 1983). The other main factors influencing stomatal conductance are vapour pressure deficit and water stress, both of which have generated considerable debate in recent times. These are discussed in more detail in the following sections.

Apparent vapour pressure or humidity deficit effects on stomatal conductance

The Penman-Monteith equation includes the vapour pressure (or density) difference between the evaporating surfaces of the leaves and the bulk air stream as the main parameter controlling the advective component of transpiration.
Despite much research, however, no physiological mechanism has been identified to satisfactorily explain this apparent dependence (Lynn and Carlson 1990; Monteith 1995; Meinzer and others 1997). Re-analysis of many published data sets by Monteith (1995) has led to the hypothesis that stomata respond to the evaporation rate itself rather than to the vapour pressure deficit. Dewar (1995) interpreted the relationship between stomatal conductance and vapour pressure deficit in terms of stomatal guard cells “sensing” transpiration rates by way of changes in the relative turgor of guard cells and epidermal cells. He also presented an alternative theory which suggested that stomatal conductance is proportional to the turgor of the guard cells themselves rather than the gradient of turgor between the guard cells and the epidermal cells.

There is still conjecture as to the nature of the transpiration rate being sensed, however. Meinzer and others (1997) reported different responses of stomatal conductance to transpiration between exposed and partially shaded poplar branches. In exposed branches, stomatal conductance (measured by porometry) declined linearly with both increasing transpiration (E) and leaf to air vapour pressure deficit (V), whereas for the partially shaded branch, the response of stomatal conductance to E was bimodal in that, as \( g_s \) declined, E increased to a maximum then also began to decline. The response to \( V \) however was again a linear decline as for the exposed branches. The response of crown conductance (calculated as the ratio of \( E \) to \( V \)) to transpiration and humidity was also investigated for the exposed and shaded branches. In both cases the response was bimodal to \( E \) and linear to \( V \). They suggested that the simplest mechanism to explain these responses to humidity is stomatal sensing of the epidermal or cuticular transpiration rate rather than the bulk leaf or stomatal transpiration rate. However, a linear relationship between \( g_c \) and \( V \) will always yield a quadratic relationship between \( g_c \) and \( E \) since \( g_c \) is derived from \( E \) and \( V \) (Monteith 1995). The linear response of stomatal conductance to \( E \) observed in exposed branches may therefore have been outer segments of quadratic responses and would have appeared bimodal if lower values of stomatal conductance had been taken. Kerstiens (1996), in a review of the physiological significance of cuticular water permeability, concluded that ultimately, the apparent humidity response may well
be a combination of both epidermal and stomatal sensing, depending on the degree of the vapour pressure deficit.

To complicate matters further, Bunce (1997) reported the elimination of stomatal responses to vapour pressure deficit in near zero carbon dioxide concentrations whereas Yong and others (1997) reported similar responses at both ambient and low CO₂ partial pressures and concluded that the nature of stomatal responses to V still remains an open question.

Not all plant species exhibit stomatal responses to vapour pressure deficit. Maroco and others (1997) studied responses of two groups of plants from the semi-arid Sahel region of Africa that exhibited different strategies of drought management. They found that drought resistant species, i.e. species which restrict water losses during drought, showed a negative response to increasing V, but in drought escaping species, which completed their life cycles between a significant rain event and the onset of the dry season, the response was independent of V. Drought resistant species are thus able to control water loss in times of high atmospheric demand while drought escaping species are able to maximise carbon dioxide uptake as long as soil moisture is not limiting. The responses of plants to conditions of limiting soil moisture are addressed in the following section.

**Water stress effects on stomatal conductance**

The movement of water through a plant from the soil to the atmosphere is governed by many physiological and environmental factors but, as long as the uptake of water by the plant is not exceeded by the loss of water from the plant, turgor will be maintained and the plant will not be water stressed (Hillel 1971). When plants become water stressed, stomatal conductance reduces sharply (Grace 1983). Water stress can occur either because of low soil moisture potential (ψₛ), high atmospheric demand (vapour pressure deficit) or low plant hydraulic conductance along the pathway between the soil and the leaves (Saliendra and others 1995).

Under non-limiting conditions plants maintain xylem potentials below the cavitation range allowing high transpiration rates. In drought conditions the
supply of water to the plant is reduced and xylem potentials can approach the cavitation range. Stomata respond by closing to limit the loss of water. If water stress persists cavitation or embolism occurs whereby xylem vessels either become air filled due to rupturing of pit membranes in the vessel walls or vapour filled due to a change of phase induced by the extreme xylem tension. In either case hydraulic conductance is reduced and may or may not be reversible.

The exact mechanism by which stomata sense changes in soil water potential has still not been satisfactorily explained but many researchers have shown that the plant hormone, abscisic acid (ABA), is in some way involved. For example synthesis of ABA in roots following drought conditions leads to an increase in xylem ABA concentration, which in turn induces stomatal closure (Tenhunen and others 1994). The reduction in conductance may alternatively be in response to a change in the amount of ABA reaching the leaves rather than the concentration per se (Gowing and others 1993). In a study on the control of leaf conductance in white lupin, Correia and Pereira (1995) found that the role of xylem ABA appeared to diminish as plant water stress due to soil drying became severe. This may suggest the involvement of other hormones (Munns and Sharp 1993). In contrast to these theories Fromm and Eschrich (1993) calculated that gas exchange responses following the application of ABA to the root system in cuttings of willow plants occurred too quickly for them to have been mediated by chemical signals through the transpiration stream. They claimed that the rapid evocation and propagation of electric signals, from action potentials following root stimulation, explained how messages from the roots to the leaves were transmitted.

Sperry and others (1993) examined the effects on stomatal conductance of reducing hydraulic conductance directly in Betula occidentalis shoots by making transverse cuts in main stems. They found that stomatal closure either reduced transpiration (E) sufficiently to prevent the xylem water potential entering the critical zone or, if E was already close to the critical zone, cavitation occurred, and embolisms were induced in the xylem. They concluded that stomatal closure probably occurred due to ABA release in the leaves following a reduction in leaf water potential below the cavitation threshold as a result of the loss of hydraulic
conductivity. Signals emanating from the roots were ruled out because the rooting environment was constant.

**Turbulence effects on stomatal conductance**

Although wind speed has been shown to influence aerodynamic or boundary layer conductance, there is evidence to suggest that these effects also influence the response of stomata by altering the state of the variables sensed by the stomatal guard cells (Aphalo and Jarvis 1993). Increased wind speed in coffee hedgerows resulted in sharp decreases in canopy conductance due to drier air being imposed at the leaf surface, changing the humidity gradient not only from the leaf surface to a reference point but also from the leaf interior to the leaf surface (Gutierrez and others 1994b). This implied that stomatal responses were only partly due to changes in vapour pressure deficit as expected and that there was an additional direct response to wind speed. This has implications for models such as the Penman-Monteith equation, which relate wind speed effects to boundary layer rather than stomatal conductance. It also raises questions as to the validity of steady state models for predicting transpiration when the frequency of turbulence events can overlap the times taken for stomatal adjustment. Grace (1983) suggests that stomata may never reach a steady aperture because the time needed for stomata to react to environmental stimuli is slow compared to the speed at which those stimuli occur. Further to this Hollinger and others (1994) showed that fluctuations in sap flow 15 m up Nothofagus trees in New Zealand lagged variations in specific humidity and temperature (caused by the imposition of turbulence events) by 1 s and 12 s respectively but at the base of the trees the lag times were 13 s and 22 s. In addition, sap flow at 15 m led sap flow at the base by 6 s, indicating some transient use of water stored within the stem. The longer lag times in temperature responses were due to the foliage heat capacity of the beech leaves. These experiments implied that atmospheric turbulence is another source of feedback on transpiration.

**The concept of critical canopy conductance**

It can be seen from the Penman-Monteith equation (Equation 3-1) that both the radiative and advective components will increase in magnitude with increasing
canopy conductance \( (g_c) \). From Equation 3-5 it can also be seen that the aerodynamic conductance \( (g_a) \) will increase linearly with increasing wind speed. Increasing \( g_a \) however, results in a decrease in the radiative component but an increase in the advective component. For there to be a net increase in \( E \), Equation 3-6 shows that canopy conductance must be greater than some critical value (Thornley and Johnson 1990; equation 14.6e);

\[
g_c = \frac{s\Phi_N}{\lambda\Delta\rho_{va}(s + \gamma)}
\]

**Equation 3-6**

At this value of canopy conductance, \( E \) is independent of any change in aerodynamic conductance \( (g_a) \). If canopy conductance \( (g_c) \) is below this value, an increase in \( g_a \) will result in a decrease in \( E \), whereas, if it is greater, an increase in \( g_a \) will result in an increase in \( E \). The effect of wind speed on transpiration therefore is bimodal, in that an increase may enhance or depress \( E \) depending on the value of \( g_c \).

The value of \( E \) at the critical canopy conductance is obtained by substituting the above value of \( g_c \) into the Penman-Monteith equation and it can be shown that this is equal to the equilibrium evaporation rate \( (E_{eq}) \) (Thornley and Johnson 1990; equation 14.6f).

**Coupling of transpiration to atmospheric and vegetative controls**

In order to highlight the relative importance of the radiative and advective components of transpiration, Jarvis and McNaughton (1986) introduced a decoupling coefficient \( (\Omega) \) with a value between 0 and 1. Evaporation from a vegetated surface \( (E) \) is then described as follows (Equation 3-7);

\[
E = \Omega E_{eq} + (1 - \Omega)E_{imp}
\]

**Equation 3-7**
where \( E_{eq} \) = the equilibrium evaporation, defined as the rate of evaporation which would occur in the absence of any diffusion gradient (Equation 3-8);

\[
E_{eq} = \frac{s\Phi_N}{\lambda(s + \gamma)}
\]

Equation 3-8

and \( E_{imp} \) = the imposed evaporation due to atmospheric and vegetative effects (Equation 3-9);

\[
E_{imp} = \frac{\rho \cdot C_p \cdot D \cdot g_c}{\lambda \cdot \gamma}
\]

Equation 3-9

The decoupling coefficient is defined in Equation 3-10 as

\[
\Omega = \frac{1}{1 + \frac{\gamma}{(s + \gamma)} \cdot \frac{g_c}{g_a}}
\]

Equation 3-10

and varies slightly with temperature through the terms \( s \) and \( \gamma \) but is determined mainly by the relative magnitudes of the aerodynamic and canopy conductances. In cases where the canopy conductance is very much greater than the aerodynamic conductance (as in low, smooth crops in low wind conditions) \( \Omega \) tends towards unity and so \( E \) tends towards \( E_{eq} \) and thus becomes decoupled from control by stomata and the effects of the atmosphere i.e. \( E \) is determined by radiation and air temperature (Whitehead and others 1984). Conversely, when the aerodynamic conductance is much greater than the canopy conductance, as in the case of tall, rough vegetation such as forests in windy conditions, \( \Omega \) tends towards zero so \( E \) tends towards \( E_{imp} \), becoming more tightly coupled to stomatal controls and the regional vapour pressure deficit of the atmosphere. Stomatal control of transpiration is greatest when the ratio of \( g_a \) to \( g_c \) is high. Meinzer and others (1995) reported values for \( \Omega \) between 0.7 and 0.9 for tropical forest in Panama.
indicating poor stomatal control of transpiration due to high $g_e$ and low wind speeds. Lee and Black (1993) on the other hand reported $\Omega$ values of around 0.2 in Douglas fir stands on Vancouver Island.

**Measuring evapotranspiration**

**Introduction**

Determining patterns of water fluxes associated with different vegetation systems requires consideration of a range of hydrological components (inputs, outputs and storages) and physical and physiological processes (evaporation, transpiration, infiltration and leaching). The choice of methods used to measure these fluxes will depend on the relative importance of the various components being studied and the scale at which the patterns are required (e.g. paddock or catchment). The available methods may be classified according to the components of the soil-plant-atmosphere continuum, which are investigated. Hydrological approaches consider the overall water balance in terms of inputs, outputs and storages and determine evapotranspiration as the residual component once the other terms have been quantified. A second approach considers the micrometeorology above and within tree canopies and determines evapotranspiration from temperature and humidity fluxes or gradients. The final category includes methods which utilise plant physiological theory and determine either evapotranspiration by measuring fluxes of water vapour from individual trees or small stands in enclosed chambers, or transpiration only by measuring sap flow through plant xylem. The remainder of this section discusses in some detail the methods described in the literature for each category.

**Hydrological approaches**

At any scale, the water balance for the soil-plant-atmosphere continuum may be represented by the following Equation 3-11;

$$E = P - D - G - RO + S$$

**Equation 3-11**
where \( E \) = evapotranspiration

\( P \) = rainfall and/or irrigation

\( D \) = downward movement of water either as drainage or groundwater recharge

\( G \) = upward movement of groundwater

\( RO \) = lateral water movement either as run-off or groundwater flow and

\( S \) = the change in soil moisture storage

For single trees or small plots, evapotranspiration may be measured using lysimeters. These are large instrumented pots, for which \( P, D \) and \( S \) can be determined and \( RO \) and \( G \) can be assumed to be zero. In the case of weighing lysimeters, evapotranspiration is assumed to be equal to the change in lysimeter weight after \( P, D \) and \( S \) have been accounted for. Similar calculations are possible for non-weighting lysimeters where water table depth is measured instead of weight. The main advantage of lysimeters is their high accuracy in determining \( ET \) of single trees (e.g. 0.05mm quoted by McIlroy and Dunin (1982); Aston (1984)) and it is this feature which makes the technique attractive to horticultural research where orchards can be considered homogeneous in terms of tree size and distribution (e.g. see Caspari and others (1993b)). In non-homogeneous forests, however, problems arise in attempting to represent natural conditions, particularly soil structure, and lysimeters must be located well inside the boundaries of plots to avoid the advective problems (heat lost by horizontal air flows) at the edges (Jensen 1990). Phreatophytic species (utilise groundwater) cannot be replicated by lysimeters due in part to their extensive root systems. Problems also arise when extrapolating single tree values of transpiration to stand or total canopy values. This is discussed later.

On a larger scale, Eastham and others (1988) measured water balance components under three spacings of *Eucalyptus grandis* plantings to determine the effect of tree spacing on the evaporation from pasture and trees in a silvopastoral system. The terms \( RO \) and \( G \) in the water balance equation were assumed to be zero.
Average annual rainfall for the region was 1099mm and actual rainfall was totalled monthly. Soil moisture changes were measured using a neutron moisture meter. The drainage component was determined from matric potential gradients and soil hydraulic conductivity, which in turn was calculated from an empirical relationship of soil moisture content, saturated hydraulic conductivity and saturated soil moisture content.

Bore hydrograph separation, a technique used to estimate groundwater recharge and discharge, was used by Salama and others (1994) to estimate long term water uptake by a river red gum plantation in Western Australia. This method allowed water use to be determined from seasonal changes in groundwater levels in wells, where comparisons of levels both within and outside the plantation could be made. Evapotranspiration was calculated as the product of the specific yield of the aquifer and the difference between the seasonal rate of change in groundwater depth below the plantation compared to that outside.

This method has the advantage of avoiding the requirement to scale up from tree to stand, since groundwater levels represent the integration of the various water balance components over the entire plantation.

It does not specifically measure plantation evapotranspiration but the difference in ET between a forested area and a cleared area i.e. the effect of reafforestation. The cleared area would still presumably have an ET component from grasses and soil evaporation, which would be different from the plantation due to the microclimatic effects of the trees i.e. grasses, if present in the plantation, would behave differently to those outside and soil evaporation would be less due to lower surface temperatures induced by shading.

For the estimation of tree water use by this method to be accurate, Salama and others (1994) list a number of criteria which need to be satisfied. These encompass the positioning of the wells, aquifer flows and the effects of barometric pressure on well levels.
**Micrometeorological approaches**

Micrometeorological approaches focus on the surface energy balance and vapour flow through the atmosphere adjacent to plants, to determine the latent and sensible heat fluxes. From these, ET can be calculated by dividing the latent heat value by the coefficient of latent heat of vaporisation of liquid water ($\lambda$). These approaches have their limitations, however, since they may only be applied in large flat areas with uniform vegetation (Denmead 1984; Bernhofer 1992). In small plantations, for instance, advection can be a large source of error in estimating evapotranspiration (Angus and Watts 1984; Salama and others 1994).

Considering the vertical energy balance at the soil surface or at the effective surface of the crop, the **Bowen Ratio technique** calculates the latent heat of evaporation as follows in Equation 3-12 (Jensen 1990);

$$\lambda E = \frac{(R_n - G)}{(1 + \beta)}$$

**Equation 3-12**

where $R_n$ = net radiation

$G$ = the heat flux density to the ground

$\beta$ = the Bowen Ratio of latent heat to sensible heat,

which may be calculated from temperature and humidity differences at two levels above the surface. The Bowen ratio method can give good results under moist conditions i.e. where the change in humidity is great relative to the change in temperature but, under drier conditions, its accuracy is limited. In addition, Denmead (1984) showed that within forest canopies, flux gradients of temperature and humidity are highly variable due to the depth of the turbulent layer. Diawara and others (1991) add that recent observations and theory suggest that flux gradients are inappropriate for studying transport within canopies and that **Eddy Correlation techniques** are more useful. Eddy Correlation equipment can
measure temperature and humidity fluxes independent of gradients (Denmead 1984). The Eddy Correlation technique measures latent and sensible heat fluxes directly by correlating fluctuations of vertical wind speed with fluctuations of temperature and vapour density (Dugas and others 1991).

Eddy Correlation estimates of evapotranspiration for wheat were found to be consistently lower than those for the Bowen ratio (Dugas and others 1991). In contrast Bernhofer (1992) reported lower estimates of evapotranspiration from a coniferous forest using the Bowen ratio technique than from Eddy Correlation at a non-ideal, sloping site. This may have been due to the stricter requirements of fetch to height ratios with the Eddy Correlation technique. Both methods are theoretically restricted to flat terrain yet studies by Nie and others (1992) showed no effect on Bowen ratio estimates of evapotranspiration on a 22° slope. They suggested that the technique should give good estimates on similar slopes.

**Plant physiological approaches**

Because there are numerous situations where micrometeorological methods are inappropriate, such as in small plantations, or where the terrain is uneven or where the vegetation is heterogeneous, the use of plant physiological approaches is warranted (Denmead 1984). These approaches include the ventilated chamber technique, which investigates gas exchange of single trees or small stands, tracer techniques, which examine the movement of heat or radioactive materials through single plants and the Combination or Penman-Monteith method. The last method estimates evapotranspiration by combining micrometeorological factors with plant physiological factors into a single formula.

**Ventilated chambers** are used to determine evapotranspiration of single trees or a few trees depending on their size. Air of known humidity is passed through the chamber and the increases in humidity of the air leaving the chamber is measured using an infra-red gas analyser (IRGA) (Rose and Sharma 1984). The method was first used by Greenwood and Beresford (1979) to measure evapotranspiration from juvenile eucalypts and has since been used by Greenwood and numerous other researchers on *Atriplex* (Greenwood and Beresford 1980), *Pinus radiata* (Greenwood and others 1981) and regenerating eucalypts (Greenwood and others
1982). Farrington and others (1992) used the technique to compare water use of agricultural and native plants in the Western Australian wheatbelt. Goulden and Field (1994) compared the ventilation chamber method with both sap flow and Penman-Monteith measurements and found that, although the chamber significantly altered the microenvironment, estimates of evapotranspiration were not significantly different. Leuning and Foster (1990) also reported a difference between the chamber microclimate and the natural environment and Denmead (1984) suggested three problem areas affected by the chamber. The solar radiation balance is upset in that the chamber walls increase net radiation. The chamber ventilation rate can affect wind speed thus affecting boundary layer conductance, and hence evapotranspiration. In addition, pressure changes induced by the ventilation rate can cause changes in the soil evaporation component in closed chambers and so bias the evapotranspiration measurements. It has been suggested that ventilation chambers alter the microenvironment but may still measure evapotranspiration accurately due to fortuitous compensating effects (Denmead and others 1993). As previously discussed in this chapter, transpiration may be enhanced or depressed by increasing wind speed depending on canopy conductance relative to a critical value. In conditions where enhancement occurs e.g. well watered, humid conditions, preventing wind access to the canopy by enclosing the tree in a ventilation chamber will therefore reduce transpiration. Conversely, in conditions of low soil moisture or high solar radiation where transpiration is depressed, enclosure will result in increased transpiration. Fortuitous compensation may occur due to the increase in solar radiation in the chamber. With no change in humidity this increases the critical canopy conductance (see Equation 3-6) which results in a reduction of transpiration enhancement where canopy conductance is above the critical value and a reduction in depression where it is below the critical value.

A combination method, which involves variations on the Penman-Monteith equation of energy balance, relates the latent heat of evaporation to both micrometeorological and plant physiological factors. Evapotranspiration may be determined from three related formulae (Denmead 1984). Firstly as shown in Equation 3-13;
\[ \lambda_E = \frac{\rho C_p [e_s(T_s) - e_a]}{\gamma (r_s + r_a)} \]

Equation 3-13

where \( \rho \), \( C_p \) and \( \gamma \) are the density of air, the specific heat of air and the psychrometric constant.

\( e_s(T_s) \) and \( e_a \) = the saturation vapour pressure at the temperature of the leaf and the ambient air vapour pressure,

\( r_s \) and \( r_a \) = leaf (or canopy) stomatal resistance and the boundary layer resistance.

This requires accurate determination of leaf temperature in order to calculate \( e_s(T_s) \), which is not easy. In addition, to characterise leaf temperature for an entire canopy requires a great number of temperature readings because of the inherent variability of temperature throughout a canopy. Similarly, although stomatal resistance (or its inverse, conductance) can be determined relatively simply using porometry or a ventilation chamber, inherent variability again necessitates extensive sampling. Stomatal resistance is dependent on numerous factors, including light, leaf water potential, temperature, humidity, \( \text{CO}_2 \) concentration and leaf age or season (Grace 1983). Boundary layer resistance is also difficult to determine for trees, because of its dependence on wind speed. Gradients of wind speed can be large and variable in profile and thus be difficult to characterise (Denmead 1984). Where stomatal resistance is significantly lower than boundary layer resistance, it is of less importance. This was also reported by Goulden and Field (1994).

A second approach, which still requires leaf temperature measurement (\( T_s \)) but not humidity or stomatal resistance, estimates latent heat losses as the difference between incident radiation (\( R \)) and sensible heat losses (\( C \)) (Equation 3-14 and Equation 3-15)
\[ \lambda E = R - C \]

Equation 3-14

where

\[ C = \frac{\rho C_p (T_s - T_a)}{r_a} \]

Equation 3-15

Incident radiation may be measured using strip radiometers for instance, although again, sampling errors may be large. Similarly, this also requires extensive sampling to characterise leaf temperature as well as accurate determination of wind speed and its relationship to boundary layer conductance.

The third approach avoids the problem of leaf temperature measurement, but in return requires a knowledge of the relationship between saturated vapour pressure and air temperature and measurement of incident radiation and air temperature. In this case the latent heat losses are calculated as shown in Equation 3-16;

\[ \lambda E = \frac{sR + \rho C_p r_a [e_s(T_a) - e_a]}{s + \gamma (1 + \frac{r_s}{r_a})} \]

Equation 3-16

where

\( s = \) the slope of the line relating saturated vapour pressure to temperature and

\( e_s(T_a) = \) the saturated vapour pressure at ambient air temperature.

This method was used by Goulden and Field (1994) to compare evapotranspiration rates from two species of evergreen oak species in California. They measured incoming radiation (R) with silicon pyranometers, air temperature
(T_r) with a thermistor, wind speed with a cup anemometer and relative humidity (e_r) with a capacitance sensor. Boundary layer conductance was calculated from a relationship with the square root of wind speed and stomatal conductance from ventilated chamber measurements. These conductances were difficult to determine but the Penman-Monteith equation was still judged to be theoretically sound. As such it is useful for making qualitative predictions of evapotranspiration (McNaughton and Jarvis 1984; Stewart 1984; Goulden and Field 1994). However, where canopies are very wet and evaporation takes place directly from leaf surfaces rather than through the stomata, estimates of ET may be poor (McNaughton and Jarvis 1984). In heterogeneous plant communities, estimates can also be poor (Rose and Sharma 1984).

The final group of plant physiological techniques uses tracers to monitor sap flow through individual plants. They measure the transpiration component rather than evapotranspiration, i.e. no estimate is made of the evaporation of water directly from plant or soil surfaces. Some methods use chemicals such as tritiated water or phosphorus ($^{32}$P) (Denmead 1984) or Deuterium ($^2$H$_2$O) (Calder and others 1986; Calder 1992), although data can be difficult to interpret and transpiration estimates can only be obtained as averages over several days (Smith and Allen 1996).

The four common methods, which utilise commercially available measurement systems, use heat as the tracer and these are extensively reviewed by Smith and Allen (1996). They are the stem heat balance method, the trunk sector heat balance method, the heat pulse (or heat pulse velocity method) and the thermal dissipation method.

By balancing the fluxes of heat into and out of a segment of stem, the mass flow rate of water in the stem (F) may be deduced using the stem heat balance method (Baker and van Bavel 1987). Heat flux into the stem is provided by a heater encircling the stem of the plant, which is then insulated, with a material of known conductivity for several centimetres above and below the heater. The mass flow rate of water is then given by the following Equation 3-17;
Chapter 3 - Tree water use and its measurement

\[ F = \frac{P - (q_u + q_d + q_r)}{C_p(T_0 - T_i)} \]

Equation 3-17

where \( P \) = the applied power.

\( q_u, q_d \) and \( q_r \) = upward, downward and radial heat fluxes,

\( C_p \) = heat capacity of water (in the xylem)

\( (T_0 - T_i) \) = the temperature differential between sap leaving the heated zone and sap entering the heated zone.

If heat is applied at a constant power rating (i.e. steady state), values for \( q_u, q_d \) and \( q_r \) can be obtained using thermocouples located above and below the heater and on the inner and outer sides of the insulation.

Alternatively, the temperature differential between the heated and unheated zones can be held constant and the power input monitored as it varies to maintain that differential. As a consequence, longitudinal and radial heat fluxes are also held constant and these can be quantified when no sap is flowing (e.g. at night) as the minimum power required to maintain the temperature differential (since no heat is lost convectively through sap flow). This approach was used by Kelliher and others (1992) to measure transpiration in a New Zealand broad-leaf forest. They found that agreement between xylem sap flow and tree canopy transpiration was reasonable (within 10-20%) when the tree canopy was dry. Tree canopy transpiration was calculated as the difference between evapotranspiration as measured by eddy covariance and forest floor evaporation measured by lysimeters.

Further evaluation of the steady state heat balance method by Baker and Nieber (1989) showed that the upward and downward conduction of heat was overestimated and radial fluxes were underestimated. As sap flow increased, heat
fluxes were poorly estimated but, because the errors were largely self-compensating, sap flow estimates were still reasonably accurate.

The steady state heat balance method was later adapted for use on small trees by Steinberg and others (1989), since it is simpler and cheaper than the constant temperature differential method, avoiding the requirement for sophisticated electronic proportional control of gauges. They reported measured sap flow rates within 4% of lysimeter rates on a small fig tree. However, Shackel and others (1992) claimed that the method was seriously flawed because it ignored naturally occurring temperature differentials on the stem. With their work on peach trees they showed that these temperature differentials are large enough to cause substantial errors in the measurement of sap flow. Khan and Ong (1995) also reported overestimation of sap flow rates due to incident radiation, increasing with the size of the trunk.

Studies by Gutiierrez and others (1994a) involved the application of extra stem insulation to reduce radiant heating and reported similar estimates of transpiration in koa and coffee plants when compared to lysimeter estimates. Ansley and others (1994) also applied extra insulation to minimise any externally induced temperature gradients in their comparative study of heat balance and porometry based measurement of transpiration from honey mesquite in Texas. In contrast, they reported considerable variation between the two methods during peak transpiration periods. Khan and Ong (1995) added extra insulation in the form of 20mm thick styrofoam to reduce errors associated with externally induced temperature gradients, but showed limitations of the technique for large stems, as expected, where steep radial gradients of temperature may occur. Howard and others (1997) used the same technique, with the extra insulation suggested by Khan and Ong (1995) to quantify water uptake in the roots of young silky oak trees.

The technique is limited to stems or branches less than about 125mm in diameter (Smith and Allen 1996). Sala and others (1996) used the technique to determine the water use of four species of phreatophytes in the Mojave desert with stems ranging from 10-40mm and Walsh and others (1995) assessed the significance of
transpiration of a *Casuarina glauca* tree with a stem diameter of 63mm, in an area affected by dryland salinity in central Queensland. Allen and Grime (1995) measured the water use of multi-stemmed savannah shrubs in Niger while Gutierrez and others (1994b) examined the regulation of transpiration in coffee hedgerows using the stem heat balance technique.

The heat balance methods assume that the surface temperature is a reliable measure of the average temperature across the entire cross section of the stem but it has been suggested that this may be incorrect at high or variable flows or in stems where the xylem is unevenly distributed (Cohen and others 1993). Ishida and others (1991) found that in monocots, where xylem is unevenly distributed in the stem, radial averaging of stem temperature significantly reduced this error in flow measurement.

The trunk sector heat balance method is in principle the same as the stem heat balance method except that it is designed for trunks with diameters greater than 120mm and heat is applied internally to only a segment of stem, rather than externally to the whole circumference (Smith and Allen 1996). Heat is applied constantly through stainless steel electrodes inserted into the trunk in parallel, almost to the heartwood boundary. Thermocouples housed in metal probes are also inserted into the sapwood. One row is situated such that one thermocouple is on each side of the middle electrode and one is outside each of the outer electrodes. The other row is situated 100mm below the first. The thermocouples are connected in series such that the voltage across them measures sap temperature increases and automatically compensates for any natural heat gradients in the stem. As in the stem heat balance method, a constant power can be applied or a constant differential can be held by regulating the power supply. The former is available commercially. Sap flow is calculated as for the stem heat balance method except that the flux from the instrumented segmented is scaled up around the entire circumference of the stem.

The technique has been used in numerous studies to measure sap flow of forest trees e.g. in oak forests on a floodplain in South Moravia, (Cermak and others 1982), Scots pine and Norway spruce in Sweden (Cermak and others 1995), laurel
forests of Tenerife, Canary Islands (Jimenez and others 1996) and Douglas fir forest in Washington state, USA (Martin and others 1997).

The thermal dissipation method, developed by Granier and others (1990), is a more simplified approach which relates sap flow almost linearly to $K$, a dimensionless sap flow coefficient (Equation 3-18);

$$K = \frac{\Delta T_m - \Delta T}{\Delta T}$$

Equation 3-18

$\Delta T$ = the temperature differential between two aluminium probes inserted into the sapwood at 150mm apart, one longitudinally above the above, with the top probe being heated at a constant rate;

$\Delta T_m$ = the same temperature differential when no sap is flowing e.g. at night.

Sap flux density (the flux per unit sapwood area) is then calculated as an empirical function of $K$, with parameters suggested to be independent of tree characteristics (Smith and Allen 1996).

Granier and others (1990) found no difference in sap flux radially in maritime pine (i.e. a number of growth rings were equally hydroactive (Goulden and Field 1994), hence total flux was calculated as the product of sap flux and sapwood area). Goulden and Field (1994) followed a similar approach working on evergreen oaks but compensated for the effect of natural longitudinal temperature gradients by installing a separate, unheated pair of probes with thermocouples adjacent to the original pair. They established that gradients were common but were successfully accounted for by the use of this technique. They reported similar rates for sap flow and evapotranspiration using a ventilated chamber but found that the relationship between sap flow and the coefficient $K$ varied, probably due to heterogeneous flow across the sapwood.
The technique has been used extensively in many studies e.g. measuring transpiration of pine forests in France (Djawar and others 1991; Granier and Loustau 1994), and of various tropical rain forest species in French Guiana (Granier and others 1996), assessing the effects of thinning on transpiration of oak forests (Breda and others 1995), investigating radial patterns of xylem sap flow in species representing three classes of wood anatomy (Phillips and others 1996) and determining the water use efficiency of oaks that differ in access to water (Goulden 1996). Meinzer and others (1997) used the technique on individual branches of four contrasting tropical tree species in Panama to investigate the stomatal control of transpiration.

A modification to the sap flow measuring system was presented by Lu (1997), who showed how more than one sensor could be monitored by the analogue input channel of the data logger, thus reducing the estimation error by 4-14 fold.

An alternative to the stem heat balance method, but still using heat as the tracer, is the heat pulse velocity method. A pulse of heat is inserted into the xylem of a plant via a heater probe and the times taken for the pulse to reach sensors, upstream and downstream of the heater are detected (Swanson and Whitfield 1981). The upstream (lower) sensor is closer to the heater than the downstream sensor, which allows the separation of the heat flux into diffusion through the woody matrix and convection by sap flow. Sap flow is derived from the convection flux (Marshall 1958) once the volume fractions of the solid wood matrix and the liquid sap have been determined.

Insertion of the heater probe and the sensor probes into the sapwood cause wounding of the tissues, locally rupturing the capillarity around the probes and thus reducing the convective flux component (Swanson and Whitfield 1981). Corrections to the sap flow velocity need to be applied to account for this wounding effect and can be done so from knowing the wound diameter.

The heat pulse velocity method has been used extensively, particularly in the southern hemisphere, where both the commercially available systems are available e.g. in eucalypt forests/woodlands and plantations (Dye and others 1992; Dunn
and Connor 1993; Dye and Olbrich 1993; Thorburn and others 1993a; Farrington and others 1994; Salama and others 1994; Barrett and others 1995; Hatton and others 1995; Dye 1996; Jolly and Walker 1996; Zang and others 1996), in pine plantations (Hatton and Vertessy 1990; Dye and others 1991, 1996; Teskey and Sheriff 1996), and in horticultural research (Edwards and Warwick 1984; Green and Clothier 1988; Caspari and others 1993a, 1993b; Green and others 1995b, 1997; Moreno and others 1996; Yunusa and others 1997). The technique has also been used successfully with other genera e.g. *Quercus* (Miller and others 1980), *Acacia* (Smith and others 1992; Vertessy and others 1995), *Melaleuca* (Mensforth and Walker 1996b), *Populus* (Smith 1992; Hogg and Hurdle 1997).

Although Granier and others (1990) reported no radial variation in sap flow velocity in maritime pine, this does not hold for most species that have so far been examined (Hatton and others 1990; Zang and others 1996). Sampling of sap velocity at several depths in the sapwood is therefore required to characterise the profile. In a study on the practicality of using the heat pulse method for measurement of transpiration in kiwifruit vines, Edwards and Warwick (1984) determined sap velocity at four depths below the cambium. These were regressed as a second order polynomial against depth and total flux was obtained by integrating this across the sapwood area, around the bole of the tree.

An alternative method by Hatton and others (1990) for determining flux from point measurements of sap velocity, weights the velocity at each depth according to the area of sapwood annulus most closely associated with each sampling depth. Total flux is then the product of the mean weighted average velocity and sapwood area. This technique was used by Dunn and Connor (1993) in a study on transpiration of old growth and regrowth mountain ash forests in Victoria, where considerable variation in sap velocity radially was found. The technique was also used on other eucalypt species by Farrington and others (1994) and Hatton and others (1995).

The technique is less sensitive to small measurement errors or random variation in sap flow velocity and is incorporated in the software used by the Greenspan® sap flow sensors (Greenspan Technologies, Warwick, Queensland). These sensors
consist of an automatic, battery operated data logger and a pair of probe kits which are inserted into the sapwood. A pulse of heat, the duration and frequency of which may be varied, is emitted by the central heater probe and the times taken for the temperature differential between the two sensor probes (above and below the heater probe) to rise above zero and to return to zero are recorded. The system may be left to operate remotely and the logged data downloaded to a portable PC at regular intervals, depending on the battery discharge rate and the heat pulse frequency. The latter determines the number of records logged (e.g. Dunn and Connor (1993) used 30 minute intervals, Salama and others (1994) 40 minutes and Farrington and others (1994) 45 minutes. The shorter the interval, the greater the number of records logged and hence more logger memory is used). The downloaded data files are then processed to determine flux by a software program SAPCAL in conjunction with an input parameter file of tree physiological measurements. These include dimensions defining sapwood area, volume fractions of woody matrix and sap, wound diameter (usually assumed to be probe diameter) and probe sensor depths into sapwood.

Greenspan sap flow sensors were used by Hatton and others (1995) for a study of poplar box (Eucalyptus populnea), in which the errors in measurement and sampling associated with sap flow monitoring were examined. These authors identified three key areas where errors may arise. Firstly, point estimates of sap flux density (velocity) are influenced by wound diameter (caused by probe insertion), volumetric wood and water contents and probe separation distance. Results showed that the total error was +/- 13%. Secondly, the integration of point estimates of sap flux across the stem requires knowledge of the area of conducting sapwood and the spatial variability of sap flux density. This can be difficult to determine according to Steinberg and others (1989), but Hatton and others (1995) showed that the error term decreases as the sample size and the number of sensors placed radially and circumferentially increases. With 32 sensors at eight depths in four trees, stratified sampling with depth gave a coefficient of variation of 16%. In a single tree with four sensors, the potential overall error rate was estimated at 38%. The final error source stems from scaling flux from individual trees to stand level and this is discussed in more detail in the next section. Depending on the scaling parameters chosen and assuming four sensors stratified by depth within six
trees stratified by diameter, the total potential error increased by a further 6% to give a maximum total error of 44%.

A primary assumption of the heat pulse method in determining sap flux is that stems are circular and that flow occurs in an annulus within the stem (i.e. between an inner and outer radius). In nature, this is obviously not strictly the case as stem cross sections may tend towards the elliptical. For the weighted average technique it has been shown that, for the eccentricities of ellipses that occur in nature, the errors associated with assuming a radial approximation instead of an ellipse are small and can be ignored (Hatton and others 1992).

The heat pulse velocity method has been shown to be a useful technique for estimating long term transpiration at the stand level, with far less supervision than for micrometeorological methods (Hatton and others 1995). Furthermore, micrometeorological and hydrological methods are also restricted by complex topography, tree height and the heterogeneity of both forests or woodlands and soil moisture conditions, leaving heat pulse measurement of sap flow as the only feasible technique for determining forest or woodland water use (Dunn and Connor 1993). The acceptability and practicality of the technique is perhaps emphasised by the proportion of tree water use studies currently being undertaken in Australia, that are utilising sap flow measurements (Nicoll 1994). This wide scale proliferation in the use of this technique has resulted in a multitude of publications, in which sap flow and its associated terminology have been reported in many different and sometimes contradictory ways. In an attempt to rationalise the terminology used in the technique, Edwards and others (1997) developed a unified nomenclature for velocities and fluxes from sap flow measurements. This nomenclature is also appropriate to the heat balance technique.

**Scaling up from single trees to stand**

The main advantage that micrometeorological and hydrological methods have over plant physiological methods is their ability to measure water use directly on an areal basis (Hatton and others 1995). Extrapolating stand or plantation water
use from monitoring of individual trees requires the use of some scaling factor (scaler), which may be determined for the entire stand or plantation.

Many scalers have been put forward, the most obvious of these being the ground area “occupied” by the tree. In an even-aged, regularly spaced monocultural plantation this has been shown to be a realistic choice (although, Hatton and Vertessy (1990) still reported a coefficient of variance of 24% in the transpiration of a pine plantation), but in native forests and woodlands the vegetation will be heterogeneous in terms of species, age and spacing and soil factors are likely to vary as well (Farrington and others 1994). In a study of transpiration in a poplar box woodland in Queensland, the area occupied by each tree (determined by a tessellation method) was found to relate very poorly to tree sap flux (Hatton and others 1995).

Area of conducting sapwood has been suggested as a useful scaler since it is logical to assume that a greater area of xylem should allow greater volumes of sap to flow through it. Sapwood area is not easy to determine for an entire plot of trees but it may be related to stem diameter, which is easily measured. In a study of transpiration rates in a Western Australian woodland stem diameter was found to be well correlated with sapwood area and was subsequently used to scale up individual transpiration rates from two eucalypt species (Farrington and others 1994). Dunn and Connor (1993) also used sapwood area as a scaler in a study on mountain ash forests and Hatton and others (1995) reported a strong relationship between flux and sapwood area in poplar box. Thorburn and others (1993a) found a linear relationship between sap velocity and sapwood area in river red gum and black box on the Chowilla floodplain but only during autumn and winter when soil water was not limiting. In summer sap velocity was independent of sapwood area and virtually constant.

To determine areal transpiration using the heat pulse technique in a red gum plantation in Western Australia, Salama and others (1994) monitored three trees of differing stem diameter and leaf area, considered to be typical of the plantation. To scale up from these three trees, other trees were classified as being equivalent to one or other of the monitored trees (according to their stem diameter and leaf
area). Total plantation water use was then calculated as the sum of the mean transpiration rates of the monitored trees weighted against the number of trees in each category. When compared to estimates of transpiration using the bore hydrograph separation technique, the heat pulse estimates were found to be lower, which is expected, since the hydrograph technique considers evaporation as well as transpiration.

As mentioned, leaf area has also been suggested as a suitable scaler of water use since water loss, as transpiration, occurs through the leaf stomata. However, many examples have been reported in the literature where the relationship between leaf area and water use is not linear (Hatton and Wu 1995). Nemani and Running (1989) suggested that a necessary equilibrium exists between climate, soil water holding capacity and maximum leaf area (in water limited coniferous forest ecosystems). Following on from this Hatton and Wu (1995) derived a general model of transpiration relating flux linearly to incident radiation and leaf area when soil moisture is not limiting and curvi-linearly to incident radiation, leaf area and soil water potential when it is. The theory was found to be consistent with measured flux/leaf area relationships reported.

**Differentiation of the sources of uptake water**

Explaining tree water use patterns in areas with shallow, saline groundwater is improved if the relative proportions of groundwater and rain derived soil water being transpired can be determined. In nature, the abundance of the naturally occurring stable isotopes of water varies because of the processes of evaporation and condensation, allowing different bodies of water to be identified according to their isotopic signatures (Ehleringer and Rundel 1989). The naturally occurring stable isotopes of hydrogen are \(^1\text{H}\) and \(^2\text{H}\) (more commonly known as Deuterium) and these will occur in different ratios in groundwater, say, compared with rainfall. Analysis of water samples using a mass spectrometer will determine the relative proportions of each.

Differentiating the source waters being taken up by plants can be achieved by comparing the isotopic signatures of xylem water with that of water extracted
from different depths in the soil profile. This has been used to explain variations in summer rainfall utilisation (Ehleringer and Dawson 1992), partitioning of sources between evergreen and deciduous species (Jackson and others 1995), between different aged trees within species (Dawson 1996), streamwater uptake (Ehleringer and Dawson 1992; Mensforth and others 1994; Thorburn and others 1994; Thorburn and Walker 1994) or groundwater use (Thorburn and others 1993a; Mensforth and Walker 1996a). The technique has been validated for determining sources of water used by plants in a semi-arid environment by Brunel and others (1995), who concluded that the total error involved in the technique appear to be less than 5%.

One of the assumptions of the technique is that fractionation of water molecules of the different isotopes does not occur when water is taken up through the roots. This was addressed by Thorburn and others (1993b) who showed that no fractionation occurs in the roots of river red gum (E. camaldulensis) during water uptake. A second assumption is that enrichment of xylem water caused by evaporation has not occurred in twig samples taken for isotopic analysis. This is critical since enrichment (i.e. an increase in Deuterium content due to evaporation of the lighter \( ^1H_2 \) molecules) will invalidate any apparent correlation between plant and source water. Problems of this nature have been identified with samples taken from young, non-suberised stems, more particularly from those of deciduous species (Dawson and Ehleringer 1993). Thorburn (1993) showed that there was very little variation in Deuterium levels in E. camaldulensis and E. largiflorens among the trunk sapwood, primary branches and big and small branches but levels measured in leaves were considerably enriched. From this it has been assumed that sampling of twigs away from leaves and fresh growth will avoid problems of enrichment.

**Summary**

Transpiration is influenced by numerous physical (atmospheric and soil related) and physiological (plant related) factors, which can act in isolation (e.g. soil moisture stress) or in combination (e.g. solar radiation, vapour pressure deficit and
Simultaneous monitoring of climatic factors and transpiration is therefore required in order to explain seasonal changes in transpiration patterns.

To evaluate the potential of interception belts, which by their very nature will be only a few rows wide, requires that transpiration patterns be determined in a number of individual trees. The heat pulse velocity technique has been shown to be appropriate for such studies and so is adopted for this study. Combining this with the stable isotopes of water technique, which enables the differentiation of the sources of water being taken up by the trees, is a proven method for determining the relative proportions of groundwater being transpired.

In saline environments the critical factors limiting transpiration are the total soil water potential (i.e. the sum of the osmotic and matric potentials) and the volume (or depth) of soil from where water may be extracted. In order to understand fully the processes controlling transpiration in these environments, studies should encompass a broad range of conditions of soil salinity.

Transpiration patterns may also vary because of the advection of wind energy onto certain trees. This is particularly the case for interception belts where the ratio of the edge length to the area of the planting will be very high compared to that of a plantation and, in a plantation, trees well away from the edge will be sheltered from the full force of prevailing winds. It is likely that most trees in an interception belt will be at or close to the edge so differences in transpiration patterns between edge trees and inner trees will be more significant in the overall water balance of interception belts relative to plantations. Again, the heat pulse velocity technique is recommended for this study.
# 4 Experimental Design

## Introduction

- General site details
- Aim and general overview
- Determination of transpiration relative to potential evaporation and rainfall
- Determination of the source or sources of uptake water
- Comparison of plantation and cleared area salt and groundwater dynamics

## Experiment 1: Transpiration patterns of *Eucalyptus camaldulensis* (Lake Albacutya provenance) along a saline gradient

- General site details
- Aim and general overview
- Determination of transpiration relative to potential evaporation and rainfall
- Determination of the source or sources of uptake water
- Comparison of plantation and cleared area salt and groundwater dynamics

## Experiment 2[a]: Variability in transpiration patterns of the Lake Albacutya provenance

- Aim and general overview
- Site details - Minlaton
- Transpiration measurement

## Experiment 2[b]: A comparison of transpiration patterns between different provenances (Lake Albacutya and Erudina)

- Aim and general overview
- Site details - Minlaton
- Transpiration measurement

## Experiment 3: The effect of wind on tree transpiration at the edge of a *Eucalyptus globulus* plantation

- Aim and general overview
- Site details
- Transpiration measurement
- Climatic monitoring

## Summary of the three experiments
Chapter 4 - Experimental Design

Introduction

To determine the usefulness of interception belts for managing water tables, a detailed knowledge of the transpiration patterns of the trees is required. It is necessary therefore to estimate the volume of water transpired and be able to predict how this will change both temporally, under seasonally varying climatic conditions, and spatially, under varying soil and groundwater conditions and specifically under planting configurations dominated by an edge or tree-pasture interfaces. In addition, to predict the relative usage of rain derived soil water and shallow groundwater requires an ability to differentiate between the possible sources of water that may be transpired.

With these aims in mind, the following experiments were conducted to investigate transpiration patterns of two commonly grown eucalypt species. The first of these, at a provenance salinity trial site at Minlaton on South Australia’s Yorke Peninsula, examined transpiration patterns of Eucalyptus camaldulensis both temporally (over a one year period) and spatially (along a saline gradient). For a shorter period during this time, intense monitoring of transpiration on other trees at the site was carried out to examine intra and inter-provenance variability. The final experiment was carried out over a 4-week period at a trial blue gum plantation in the south east of South Australia and aimed at examining possible edge effects of increased wind advection on transpiration rates.

In the remainder of this chapter each experiment is described in detail and the components of each and how they are related are illustrated in Figure 4-1, Figure 4-2 and Figure 4-3.
Figure 4-1: Overview of experimental procedure;

- $E_t = \text{transpiration on an areal basis (heat pulse velocity technique)}$
- $E_{\text{tp}} = \text{potential transpiration (as estimated by Priestley-Taylor Equation)}$
- $R = \text{ratio of } E_t : E_{\text{tp}}$
- $T = \text{total soil water potential profile}$
- $I = \text{source of water transpired (stable isotopes of water technique)}$
- $G = \text{groundwater depth and salinity}$

1. Transpiration patterns along a saline gradient

- How do $E_t$ and $R$ vary seasonally along a salinity gradient?
- How are they partitioned seasonally between soil water and groundwater along this gradient?
- How do soil and groundwater conditions differ seasonally along saline gradients that are under the influence of trees compared to those that are not?

- $R$ determined daily for 5 trees along a saline gradient over a 12 month period
- $G$ determined regularly at 3 sites along each of 2 saline gradients, one with and one without the influence of trees over a 12 month period
- $I$ determined at 3 sites along a saline gradient on 5 occasions over 12 months to quantify the ratio of soil water to groundwater being transpired
- $T$ determined at 3 sites along a saline gradient on 5 occasions over 12 months

Series of partitioned $R$ values at discrete time intervals of soil water potential conditions

Series of comparisons of soil and groundwater conditions at discrete time intervals along saline gradients

Outcome: determination of seasonal water use patterns and the likely effectiveness of interception belts
Figure 4-2: Overview of experimental procedure;

\[ Q_s = \text{sap flux per unit sapwood area (heat pulse velocity technique)} \]

2. Variability in transpiration patterns along a saline gradient

How does \( Q_s \) vary within and between provenances?

- \( Q_s \) replicated for trees of the same provenance at 3 equivalent contour positions
- \( Q_s \) determined for a parallel transect of 3 trees of a second provenance

Outcome: determination of the variability of transpiration rates within and between provenances
Figure 4-3: Overview of experimental procedure;

\[ E_i = \text{transpiration on an areal basis (heat pulse velocity technique)} \]

\[ E_{ip} = \text{potential transpiration (as estimated by Priestley-Taylor Equation)} \]

\[ R = \text{ratio of } E_i : E_{ip} \]

**3. Edge effects on transpiration due to advection of wind energy**

*How does \( R \) vary with respect to tree position in a belt or plantation?*

\( R \) determined for trees at different distances from the edge of a plantation on a daily basis.

*Outcome: determination of the edge effect of wind on transpiration and a general indication of interception belt configuration*
Chapter 4 - Experimental Design

Experiment 1: Transpiration patterns of Eucalyptus camaldulensis (Lake Albacutya provenance) along a saline gradient

General site details

This and the following two experiments were carried out on a property at Minlaton (34° 45' S, 137° 35' E) on South Australia’s Yorke Peninsula, to the west of Adelaide. The climate is typically Mediterranean, with hot, dry summers and a winter dominant rainfall (average = 442mm). The soil is generally a shallow duplex with approximately 70-80cm sand over a heavy clay.

A selection of 11 river red gum (Eucalyptus camaldulensis) provenances were planted along a slope up from a saline lake in 1986 by the South Australian Woods and Forests Department (now Primary Industries and Resources S.A.). The trees were planted on a 3m x 3m grid in transects of 6-8 trees per provenance with a double row of the Lake Albacutya provenance bordering the entire plantation (see Figure 4-4). The original aim of the trial was to assess the salinity tolerance and growth performance of the various provenances (Dalton, unpub.).

Figure 4-4: Plan of the red gum plantation at Minlaton. Rows are 3m apart and Row 9 is 10m from the edge of the saline lake. Transect RG1 to RG5 (running roughly N-S) = Lake Albacutya provenance trees used in experiment 1, large open circles = other Lake Albacutya provenance trees, small circles = other provenances of E.camaldulensis, Y = E.occidentalis trees, S = Allocasuarina verticillata trees, * = dead or missing trees, R1, R2, R3 = piezometers installed July 1996, + = old piezometers.

When the plantation was first visited in July 1996 nearly all the trees in the first two rows closest to the lake edge were dead. In the surviving rows, there was still
a well defined gradient in tree size leading away from the lake (Figure 4-5), suggesting a response to salinity.

Figure 4-5: The red gum provenance salinity trial site at Minlaton, showing the gradient in tree size increasing from left to right

At the time of planting, six piezometers had been sunk to 1.5m within the plantation to monitor groundwater levels but by 1996 these were often dry. To allow continued monitoring of the groundwater all year round, a further three piezometers (R1, R2, R3) were installed to a depth of 3m within the plantation at the beginning of this experiment in July 1996. To enable a comparison of the behaviour of the water table below the trees with that outside the plantation, another three (C1, C2, C3) were installed some 80m around the lake at similar distances from the lake edge, but beyond the influence of any trees. Here, the vegetation consisted of sparse tall wheat grass (*Agropyron elongatum*) and other seasonal grasses.

An automatic weather station was installed on site in August 1996 and was used to monitor air temperature, solar radiation and rainfall for the duration of the experiments. Apart from a short period in September and October 1996 when the solar panel failed, weather data was logged continuously for 12 months.

**Aim and general overview**

The aim of this experiment was to investigate seasonal patterns of transpiration along a saline gradient in terms of the partitioning of different sources of
water and also in response to the dynamic nature of soil and groundwater conditions. By measuring the transpiration of individual trees at discrete points along a saline gradient it should be possible to determine certain critical dimensions (such as distance from the saline lake edge or depth to water table) which are required to sustain optimal water removal rates.

Transpiration itself, however, can be highly variable, being responsive not only to prevailing climatic conditions but also to the availability of water to the tree roots, i.e. from rain derived soil water or from shallow groundwater. Simultaneous monitoring of climatic conditions and transpiration is therefore required to predict how transpiration rates may vary seasonally and a means of determining the source of water being transpired will allow an estimate to be made of how these sources are partitioned. This in turn will assist in the selection of optimal locations for interception belts in the landscape to maximise water removal.

Limitations on transpiration due to excessive soil water potential can be expected where soils become too dry or where solute concentrations in the soil become too high. Conditions such as these may occur as a result of direct evaporation from the soil surface following capillary rise or as a result of high rates of transpiration. In the latter case salinisation of the root zone by the trees will obviously be counter-productive as far as maintaining high water removal rates is concerned, whereas the shading effect and deep rooted nature of trees is likely to limit direct soil evaporation. In order to distinguish between such effects, it becomes necessary to examine the seasonal changes in soil and groundwater conditions both with and without the influence of trees.

The following describes in detail how these criteria were addressed experimentally.

**Determination of transpiration relative to potential evaporation and rainfall**

For the first experiment a transect of the Lake Albacutya provenance was selected for transpiration monitoring (Figure 4-6). Five trees were available in this transect and these showed a marked increase in stem diameter and leaf area upslope. Data to determine transpiration of these five trees were collected over a 12-month period using the heat pulse
velocity technique with commercially available Greenspan™ loggers. Three versions of loggers were used with two different probe configurations.

![Figure 4-6: Transect of river red gums instrumented with sap flow sensors. The saline lake is in the background.](image)

These are displayed in Table 4-1 along with the depths of insertion of the probes into the trees and the dimensions of the relevant physical parameters of the trees, required to calculate fluxes from sap flow densities. The loggers were set to record at 30-minute intervals and the resultant data files were downloaded to a portable laptop computer approximately every three weeks. Daily transpiration rates were calculated using a custom-designed spreadsheet macro in Microsoft Excel™.
Table 4-1: Tree parameters and logger details for Experiment 1

<table>
<thead>
<tr>
<th>Tree ID</th>
<th>Diam (mm)</th>
<th>bark depth (mm)</th>
<th>cambium radius (mm)</th>
<th>heartwood radius (mm)</th>
<th>sapwood area (cm²)</th>
<th>Greenspan™ logger version and type</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG1</td>
<td>350</td>
<td>16</td>
<td>159</td>
<td>62</td>
<td>673</td>
<td>2 split</td>
</tr>
<tr>
<td>RG2</td>
<td>150</td>
<td>7</td>
<td>68</td>
<td>25</td>
<td>126</td>
<td>2 split</td>
</tr>
<tr>
<td>RG3</td>
<td>130</td>
<td>6</td>
<td>59</td>
<td>25</td>
<td>90</td>
<td>2 standard</td>
</tr>
<tr>
<td>RG4</td>
<td>136</td>
<td>6</td>
<td>59</td>
<td>25</td>
<td>111</td>
<td>1 standard</td>
</tr>
<tr>
<td>RG5</td>
<td>68</td>
<td>6</td>
<td>28</td>
<td>0</td>
<td>25</td>
<td>1 standard</td>
</tr>
</tbody>
</table>

A Monitor Systems™ automatic weather station recorded maximum and minimum air temperatures, solar radiation and rainfall and logged these on a daily basis. The Monitor™ software was then used to calculate Priestley-Taylor values of potential evaporation, against which daily values of transpiration could be compared. For a more detailed explanation of the formulae used to calculate potential evaporation, refer to chapter 7 (pp.129-131).

**Determination of the source or sources of uptake water**

Where trees have access to two sources of water i.e. rain derived soil water and shallow groundwater, it is important to ascertain the relative proportions of these sources that the trees are likely to be using in order to gauge how effective they may be in lowering water tables. In the most effective case trees may transpire the groundwater directly, in which case a source may be available year round. Alternatively, they may prevent recharge to the water table by transpiring soil water only. This can be seasonally limiting in that water may become less available towards the end of summer, thus reducing transpiration, and in excess during winter when atmospheric demand, and hence transpiration, is low.

For this experiment, the sources of water taken up were determined directly by comparing the relative deuterium contents of twig water samples to those of groundwater and of water extracted from the soil (as per Ehleringer and Dawson (1992)). This technique was then augmented by inferring the likely sites of root extraction of water indirectly from total soil water potential profiles (Thorburn and others 1993a; Mensforth and others 1994).
Soil was first sampled from cores removed during the installation of the piezometers on 31/7/96 (R1, R2, R3 on Figure 4-4 and C1, C2, C3). Samplings at subsequent visits were made close by at points on the same contours of the original cores i.e. perpendicular to the salinity gradient. The soil profile was augered and soil removed at specified increments, then stored in airtight, glass jars to prevent any evaporation loss and retained for laboratory analysis. At each visit a sample of the groundwater was taken from the three piezometers within the plantation and similarly sealed in a glass jar. Some twig samples were taken from each of the five trees and these were sealed in glass jars containing kerosene.

The sampling dates were selected with the intention that differences in soil and groundwater conditions, and hence, changes in transpiration patterns would be most pronounced. The first sampling therefore was in winter (July 1996) when it was expected that the soil profile would have been fully saturated and leached of salt, and the trees would have been transpiring little due to low atmospheric demand. The second sampling in spring (October 1996) was designed to detect changes in transpiration rates due to the increase in atmospheric demand, combined with a period of vegetative growth. By the third sampling at the end of summer (March 1997) it was expected that the soil profile would be at its driest and this was potentially the most likely time of year to detect the trees using groundwater. The fourth sampling (May 1997) was timed to coincide with the onset of winter rains when the trees would be able to access rain water near the soil surface in addition to or instead of groundwater. The final sampling in the second winter (August 1997) was designed to complete the cycle and show again the change of water extraction from groundwater to rain-derived soil water.

The relative deuterium content of the soil, groundwater and twig samples at each sampling was measured by mass spectroscopy and used to determine the source of water being taken up by the trees. A distillation technique was first used to extract water from the soil, twig and groundwater samples (Revesz and Woods 1990; Thorburn and others 1993b). Samples were heated with kerosene in a Dean-Stark apparatus and allowed to boil for two hours. At this temperature water and kerosene in the gaseous phase form an azeotropic mixture, which ensures the removal of all the water from the sample at the condensation stage. The extracted water samples were drained from the apparatus into McCartney bottles and excess
Kerosene was removed with the addition of paraffin wax that also acted as a seal. Subsamples of the extracted water were heated and passed over a depleted uranium source to produce hydrogen gas prior to being injected into the mass spectrometer. The difference in deuterium content (δD) relative to a sample of the international Standard Mean Ocean Water (SMOW) was reported in parts per thousand (%). Soil water and groundwater generally have different isotopic signatures, particularly for surface soils where evaporation results in enriched deuterium levels. The source of water being taken up by the trees may be identified directly where the δD value of the twigs corresponds to that of either enriched surface soils or depleted deeper soil water/groundwater. Where the δD values of the twig extracts lie between the extreme values of the soil and groundwater extracts, it may be possible to infer the relative proportions being transpired by examination of the total water potential of the soil profiles. Tree roots will extract water from zones of least negative potential, hence, by combining the δD values of the soil at these zones and comparing them with those of the twig extracts, the relative proportions of the source waters being transpired may be determined.

In order to assist in the determination of the source water and also to characterise the soil profiles along the saline gradient, total soil water potential, as the sum of soil matric and osmotic potential, was determined for each soil sample.

Soil matric potential was determined using the filter paper technique of Greacen and others (1989). Three Whatman No.42 filter papers were placed in each of the samples and allowed to equilibrate at 20° C for six days. The filter papers were then weighed, dried in an oven then reweighed, and matric potential was calculated as a function of the amount of water absorbed by the papers.

Soil osmotic potential was determined from a relationship using the electrical conductivity of a 1:5 soil water solution (EC1:5) and the gravimetric soil moisture content θg. Subsamples of each soil were weighed wet (Wwet), dried at 105° C then reweighed 24 hours later (Wdry) and the gravimetric water content determined from Equation 4-1;
A further subsample of 20g of the oven dried soil was then taken and added to 100mL of de-ionised water. The mixtures were then shaken for 1h in an end-over-end shaker and allowed to settle. The electrical conductivity (corrected for temperature) of the resultant supernatant was then recorded. Osmotic Potential ($\psi_s$) can be calculated as a linear function of conductivity using Equation 4-2 modified from Shainberg and Oster (1978) as follows;

$$\psi_\Pi (kPa) = 0.36 \times 101.3 \times EC$$

where the factor 101.3 converts $\psi_s$ in atmospheres to kPa but must be corrected to account for the dilution factor by multiplying by $100 / (20 \times \theta_g)$ i.e. the ratio of water added to the oven dried 20g sample to that originally present in the sample. Total soil water potential was then summed from the matric and osmotic components and plotted against depth to characterise the profile.

Comparison of plantation and cleared area salt and groundwater dynamics

In order to facilitate a comparison between the plantation and the cleared areas in terms of salt and water dynamics, total soil water potential profiles were determined (as described previously) for the three sites within the plantation, R1, R2 and R3 (see Figure 4-4) and the three sites outside, C1, C2 and C3. In addition, the depth of the groundwater from the top of the piezometer casing and the electrical conductivity of samples drawn from the piezometers were monitored over the 12 month period at approximately three week intervals.
Experiment 2[a]: Variability in transpiration patterns of the Lake Albacutya provenance

Aim and general overview

Predicting the effectiveness of interception belts can be achieved with greater confidence where the variability of transpiration per unit length of belt is known to be low. This experiment investigates how transpiration rates, as a function of sap flux per unit sapwood area ($Q_s$), vary among contours, perpendicular to the saline gradient.

Site details - Minlaton

The Minlaton site was again used for this experiment (see Experiment 1 for general site details). Figure 4-7 shows the relative positions of the trees used.

Figure 4-7: Plan of plantation at Minlaton showing trees used in experiment 2 (underlined). All numbered trees are Lake Albacutya provenance used in experiment 2[a] except for M3.10, M4.10, M6.10 which are provenance Erudina used in experiment 2[b]. (Note that trees RG1 to RG5 from experiment 1 have been renumbered as M1.11 to M5.11 for convenience). Other legend items are as per Figure 4-4.

Transpiration measurement

Transpiration of Lake Albacutya provenance red gums was monitored, again using the heat pulse velocity technique at three contours running parallel to the lake edge for the period 17/10/96 to 11/11/96. Six trees were monitored in row 2 and
two in each of rows 3, 4 and 5 (see Figure 4-7). Table 4-2 shows the relevant physical parameters of each tree.

<table>
<thead>
<tr>
<th>Tree ID</th>
<th>Row Number</th>
<th>Diameter (mm)</th>
<th>Bark Depth (mm)</th>
<th>Cambium Radius (mm)</th>
<th>Heartwood Radius (mm)</th>
<th>Sapwood Area (cm²)</th>
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<td>62</td>
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<td>111</td>
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<td>54</td>
<td>17</td>
<td>83</td>
</tr>
<tr>
<td>M5.11</td>
<td>5</td>
<td>64</td>
<td>4</td>
<td>28</td>
<td>0</td>
<td>25</td>
</tr>
<tr>
<td>M6.2</td>
<td>6</td>
<td>114</td>
<td>5</td>
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<td>17</td>
<td>76</td>
</tr>
</tbody>
</table>

Table 4-2 : Tree parameters for Experiment 2[a]
Experiment 2[b]: A comparison of transpiration patterns between different provenances (Lake Albacutya and Erudina)

Aim and general overview

_Eucalyptus camaldulensis_ is a commonly planted species used for bioremediation of saline agricultural catchments but the water use characteristics of individual provenances have been shown to vary according to site characteristics (Farrell and others 1996; Akilan and others 1997; Marshall and others 1997). This site provided an opportunity to compare simultaneously the transpiration rates of other provenances of red gum under the same conditions. The experiment investigates how transpiration rates of two of the provenances, Lake Albacutya and Erudina, vary along a saline gradient. Only one other provenance was investigated because of the limited availability of sap flow sensors and Erudina was chosen because of the suitability and number of the surviving specimens of this provenance for the heat pulse velocity technique.

Site details - Minlaton

The Minlaton site was again used for this experiment (see Experiment 1 for general site details). Figure 4-7 shows the relative positions of the trees used.

Transpiration measurement

As for the two previous experiments, transpiration was again monitored using the heat pulse velocity technique. Three trees from each of the two provenances were instrumented for the period 17/10/96 to 11/11/96. Table 4-3: Tree shows the relevant physical parameters for each tree.
### Table 4-3: Tree physical parameters for Experiment 2[b]

<table>
<thead>
<tr>
<th>Tree ID</th>
<th>Red gum Provenance</th>
<th>Diameter (mm)</th>
<th>Bark Depth (mm)</th>
<th>Cambium Radius (mm)</th>
<th>Heartwood Radius (mm)</th>
<th>Sapwood Area (cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>M3.10</td>
<td>Erudina</td>
<td>110</td>
<td>11</td>
<td>44</td>
<td>11</td>
<td>57</td>
</tr>
<tr>
<td>M4.10</td>
<td>Erudina</td>
<td>88</td>
<td>6</td>
<td>38</td>
<td>6</td>
<td>44</td>
</tr>
<tr>
<td>M6.10</td>
<td>Erudina</td>
<td>80</td>
<td>5</td>
<td>35</td>
<td>5</td>
<td>38</td>
</tr>
<tr>
<td>M3.11</td>
<td>L.Albacutya</td>
<td>130</td>
<td>6</td>
<td>59</td>
<td>25</td>
<td>90</td>
</tr>
<tr>
<td>M4.11</td>
<td>L.Albacutya</td>
<td>136</td>
<td>6</td>
<td>62</td>
<td>18</td>
<td>111</td>
</tr>
<tr>
<td>M6.2</td>
<td>L.Albacutya</td>
<td>114</td>
<td>5</td>
<td>52</td>
<td>17</td>
<td>76</td>
</tr>
</tbody>
</table>
Experiment 3: The effect of wind on tree transpiration at the edge of a Eucalyptus globulus plantation

Aim and general overview

It is hypothesised that, in a belt or plantation of trees, transpiration rates will be greater for trees situated at the edge due to the effect of reduced competition from fewer immediate neighbours and a potentially greater advective effect due to less sheltering of wind. It is reasonable to assume that edge trees will exhibit greater growth rates due to the enhanced access to soil rooting volume, photosynthetically active radiation (PAR) and other growth influencing factors and that this will be reflected in larger sapwood area and leaf area. Both these parameters show excellent linear correlation with transpiration (e.g. Hatton and others (1995); Vertessy and others (1995)) and may be used as scaling or normalising factors to enable the comparison of trees of different sizes, thus neutralising differences in water use (in absolute terms) due to long term growth effects.

If transpiration rates are normalised against either leaf area or sapwood area, they may still be higher for edge trees in the short term due to differences in water availability or greater advection of wind energy. The degree of such effects has implications for the design of interception belts. Indications of reduced transpiration due to periodically insufficient water availability would tend to favour a reduced planting density to allow greater rooting volume per tree. If advection strongly influences tree water use, belt design would tend to favour widely spaced, single rows, where the available wind energy could be utilised most effectively by all the trees. Conversely, if there is little influence due to advection, design would more likely favour denser, multi-row belts, to maximise water use and also provide a more valuable forest product. The following field-based experiment was conducted to determine if there is an effect of tree position in a belt or plantation on transpiration rate, and if so, how important it is and at what distance from the edge this effect becomes negligible.
Site details

A 7-year-old Tasmanian blue gum (*Eucalyptus globulus*) plantation at Talinga 35 kms north of Naracoorte (36.96 S, 140.74 E) in the south east of South Australia was selected for conducting the experiment.

The 2 ha plantation had originally been planted to assess the potential of the species for pulpwood production in a rainfall zone of less than 600mm. The plantation was approximately 200 m long by 100 m wide, with the long axis running north-south rising slightly at the northern end onto an east-west dune. Otherwise, the land around the plantation was reasonably flat with a wheat crop on the western and southern sides and sheep pasture to the east.

Trees were planted on a 3m x 3m grid and had reached an average height of 14 m with a completely full canopy by the start of the experiment. Some gaps were apparent where trees had not survived but all trees sampled had a full complement of neighbours (i.e eight for inner trees and five for edge trees). The experiment was conducted over the period 4 December 1996 to 3 January 1997, at which time it was expected that transpiration by the trees would be at a maximum due to the combination of high evaporative demand and a plentiful soil water supply after winter.

Transpiration measurement

Greenspan™ sap flow sensors were installed on 16 trees on a transect from the western edge to the eastern edge of the plantation and programmed to log continuously at 30 min intervals. Tree parameters measured to enable sap fluxes to be calculated were circumference at breast height, bark thickness, depth to heartwood and volumetric wood and water contents of cored sapwood samples. Table 4-4 shows the relevant physical parameters of the selected trees and their positions in the plantation.
Table 4-4: Tree parameters for Experiment 3.

Climatic monitoring

A 15-m tower was erected at the western edge to support meteorological equipment used to monitor a range of parameters above the tree canopy. These were air temperature and humidity, solar radiation, wind speed and wind direction, all of which were averaged and logged automatically over 15-min intervals for the duration of the experiment. Rainfall was recorded at ground level. A second tower housing wet and dry bulb temperature sensors and an anemometer was erected at the eastern edge of the plantation in order to compare entry and exit humidity and wind speeds to and from the plantation.
Unfortunately, failure of the datalogger and subsequent corruption of the data file resulted in no useful data being retrieved from this tower.

Figure 4-8: Talinga blue gum plantation view, showing location of tower on western boundary.
Summary of the three experiments

The program of field based experiments for this project focuses on transpiration patterns of *Eucalyptus camaldulensis* at a trial site at Minlaton, South Australia. It investigates these patterns for the Lake Albacutya provenance firstly under the influence of a saline gradient in experiment 1, then in the absence of a gradient in experiment 2. Transpiration patterns of a second provenance, Erudina, are also compared with the Lake Albacutya provenance in this experiment. The third experiment, in the south east of South Australia, investigates the effect of wind on transpiration rates at the edge of a *Eucalyptus globulus* plantation.

The following three chapters present the results and some preliminary discussion of these experiments. The first of these, chapter 5, is a precursor to the others in that it critically examines the available methods of analysing data files generated by the heat pulse velocity technique and presents a new method to minimise errors. Using this novel technique, the results and some preliminary discussion of experiments 1, 2 and 3 are then presented in chapters 6 and 7.
# Chapter 5 - Analysis of heat pulse data files

5 Analysis of data generated by the heat pulse velocity technique

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<tr>
<th>Section</th>
<th>Page</th>
</tr>
</thead>
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<td>78</td>
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<tr>
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<td>80</td>
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<tr>
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<td>83</td>
</tr>
</tbody>
</table>
Introduction

Processing of the raw data files, generated by the heat pulse sap flow loggers, involves converting a series of point estimates of heat pulse velocity to total tree fluxes. Preliminary analysis of these files, however, indicated that, in certain cases, fluxes could be overestimated using conventional analyses. In this chapter, a novel technique for determining daily sap fluxes from sap velocities measured at discrete points is presented. This technique is more robust in that it overcomes the problems that can arise where the installation of the probe sets results in non-uniform sampling of the sapwood depth.

Background

The heat pulse velocity technique yields sap velocity at a number of discrete points within the sapwood. To calculate whole tree transpiration rates from these velocities, however, requires certain assumptions to be made regarding the characterisation of the velocity profile both radially and around the bole of the tree. The cross section of the stem can be assumed to be circular (Hatton and others 1992) so that fluxes may be calculated by integrating the radial velocity profile around the stem. Characterising this velocity profile from a series of point estimates is problematic and researchers have devised different means to address this.

Edwards and Warwick (1984) determined sap velocity in kiwifruit vines at four depths below the cambium. These were regressed as a second order polynomial against depth and total flux was obtained by integrating this across the sapwood area, around the bole of the tree. Problems arise when the fitted velocity profile intersects the radial axis at points other than the heartwood and cambium radii.

The weighted average technique (Hatton and others 1990) divides the sapwood annulus into a series of smaller annuli, encompassing each sensor, and weights the sap velocity determined at each sensor to its appropriate annulus, according to the relative area of that annulus. Care must be taken to install the probes such that they sample the entire depth of sapwood uniformly. In certain situations this may prove difficult to
achieve. The standard Greenspan™ probes are 50mm long and have two sensors set at 5mm and 10mm from the end. For trees where the sapwood is more than about 30mm deep, it becomes increasingly difficult to sample uniformly. Even with the split probe single sensor units (as used on trees RG1 and RG2), uniform sampling becomes impossible for trees with deep sapwood.

Figure 5-1 shows an example of how the velocity profile may be characterised by these two methods for measurements made at four depths in the sapwood. Note how both methods apply positive velocities at the cambium radius (CR) and, while the polynomial integration curve can intercept the radial axis within the sapwood leading to zero flux in that region, the weighted average curve applies a positive velocity through to the heartwood radius (HR). This in itself does not imply that the weighted average technique overestimates flux. Flux is calculated by integrating the measured point velocity around the bole of the tree for each annulus, producing a series of step functions as shown in Figure 5-1.

![Figure 5-1: Velocity profiles characterised from 4 point measurements (▲) by the weighted average technique (solid line) and the polynomial integration method (dotted line).](image)

Providing that the sum of the overestimates of the integrals is matched by the sum of the underestimates between each pair of adjacent sensors, then the method is robust.
Examination of the inner and outermost sensors in Figure 5-1 suggests that the integration of velocities measured at those points would lead to overestimates of fluxes within their respective annuli. In practice, without prior knowledge of the velocity profile, it can be difficult to ensure that the sensors are placed well enough to avoid this problem. Even with prior knowledge, the configuration of the standard probe sets (i.e. two sensors at 5mm apart) can make it impossible to achieve satisfactory placement. The problem can be partially overcome using split probe sets which have only a single sensor on each probe, facilitating more accurate placement of individual sensors. If, in hindsight, it is discovered that the sensors have not been placed accurately enough, analysis using the weighted average technique may yield errors.

**Introducing the velocity area method**

For these reasons an alternative method was devised, whereby the sap flux is determined by integrating around the bole of the tree a set of linear functions of velocity derived from point measurements made at each sensor. These velocity functions are calculated from the area under the velocity versus sensor implantation depth curve and assume a linear change in velocity between adjacent sensors and zero flow at the cambium and heartwood radii, as shown in Figure 5-2. In the absence of any other knowledge regarding the shape of the radial velocity profile, a simple assumption of linearity between sensors, although improbable in reality, is reasonable in that it yields the most parsimonious estimates of flux.
The total daily flux can be expressed as follows in Equation 5-1

\[
Q = \int_{HR}^{CR} 2\pi r v(r) \, dr
\]

Equation 5-1

where \( CR \) = cambium radius, \( HR \) = heartwood radius and \( v(r) \) describes sap velocity as a function of the radius. Velocity is assumed to vary linearly between sensors, hence a simple expression (Equation 5-2) can be derived which relates sap velocity to radial distance for any point between the heartwood and cambium radii thus

\[
v = S_i \cdot r - S_i \cdot r_i + v_i
\]

Equation 5-2

where

\[
S_i = \frac{v_i - v_{i-1}}{r_i - r_{i-1}}
\]
is the change in measured sap velocity from the sensor at radial distance \( r_{i-1} \) to the sensor at \( r_i \). The flux calculated by the velocity area method (\( Q_{va} \)) can then be written as the sum of a series of individual integrals (Equation 5-3).

\[
Q_{va} = \sum_{i=1}^{n+1} \int_{r_{i-1}}^{r_i} 2\pi r \left( s_i \cdot r - s_i \cdot r_i + v_i \right) dr
\]

where \( n \) = the number of sensors, \( r_n \) becomes the cambium radius and \( r_0 \) the heartwood radius. Note that there are \( n+1 \) integrals to sum because the \( n \) sensors divide the sapwood radially into \( n+1 \) segments. The resultant series of third order polynomial functions to which this eventually reduces is easily incorporated into a spreadsheet, requiring only the radial distance and corrected sap velocity at each sensor to estimate sap flux. Note that like the polynomial integration and weighted average techniques, this technique is not limited to any particular number of sensors.

**Comparison of weighted average and velocity area methods**

Daily fluxes were calculated using the data files generated by the sap flow loggers and a set of measured parameters for each tree (cambium radius, heartwood radius, bark thickness, probe insertion depths and volumetric wood and water contents). Sap velocities, corrected for wounding and relative wood and water contents, were determined for each sensor. The weighted average and velocity area methods were then employed to convert these velocities to fluxes. Table 5-1 shows that the velocity area method consistently yields lower fluxes than the weighted average technique (\( Q_{va} : Q_{wa} \) ratio always less than one), yet the ratio of the fluxes derived from each method is not consistent amongst trees (0.30 - 0.91). The low standard deviations of means indicate that the variations in flux measurements between the two methods were independent of the absolute flux values on a given day.
### Table 5-1: Average ratio of daily tree water use as determined by the velocity area method ($Q_{va}$) to that determined by the weighted average technique ($Q_{wa}$) for trees at the Minlaton site (over 12 months) and the Talinga site (over two logging periods).

<table>
<thead>
<tr>
<th>TREE IDENT.</th>
<th>Average $Q_{va}: Q_{wa}$</th>
<th>Standard deviation</th>
<th>Number of days sampled</th>
</tr>
</thead>
<tbody>
<tr>
<td>RG1</td>
<td>0.68</td>
<td>0.02</td>
<td>316</td>
</tr>
<tr>
<td>RG2</td>
<td>0.91</td>
<td>0.03</td>
<td>293</td>
</tr>
<tr>
<td>RG4</td>
<td>0.75</td>
<td>0.04</td>
<td>282</td>
</tr>
<tr>
<td>RG5</td>
<td>0.30</td>
<td>0.10</td>
<td>286</td>
</tr>
<tr>
<td>W01A</td>
<td>0.76</td>
<td>0.01</td>
<td>13</td>
</tr>
<tr>
<td>W01B</td>
<td>0.69</td>
<td>0.02</td>
<td>13</td>
</tr>
<tr>
<td>W02B</td>
<td>0.69</td>
<td>0.03</td>
<td>13</td>
</tr>
<tr>
<td>W05</td>
<td>0.80</td>
<td>0.04</td>
<td>12</td>
</tr>
<tr>
<td>W09</td>
<td>0.78</td>
<td>0.02</td>
<td>12</td>
</tr>
<tr>
<td>W13</td>
<td>0.59</td>
<td>0.02</td>
<td>12</td>
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<tr>
<td>W17</td>
<td>0.82</td>
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<td>E16</td>
<td>0.80</td>
<td>0.00</td>
<td>12</td>
</tr>
<tr>
<td>E12</td>
<td>0.75</td>
<td>0.02</td>
<td>12</td>
</tr>
<tr>
<td>E09</td>
<td>0.65</td>
<td>0.02</td>
<td>12</td>
</tr>
<tr>
<td>E02B</td>
<td>0.61</td>
<td>0.01</td>
<td>12</td>
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<tr>
<td>E02A</td>
<td>0.71</td>
<td>0.02</td>
<td>12</td>
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<td>E01B</td>
<td>0.86</td>
<td>0.02</td>
<td>12</td>
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<td>0.01</td>
<td>12</td>
</tr>
<tr>
<td>W01B</td>
<td>0.75</td>
<td>0.01</td>
<td>16</td>
</tr>
<tr>
<td>W01A</td>
<td>0.75</td>
<td>0.01</td>
<td>16</td>
</tr>
<tr>
<td>W02A</td>
<td>0.91</td>
<td>0.03</td>
<td>14</td>
</tr>
<tr>
<td>W02B</td>
<td>0.69</td>
<td>0.06</td>
<td>8</td>
</tr>
<tr>
<td>W05</td>
<td>0.78</td>
<td>0.06</td>
<td>14</td>
</tr>
<tr>
<td>E12</td>
<td>0.73</td>
<td>0.02</td>
<td>16</td>
</tr>
<tr>
<td>E05</td>
<td>0.71</td>
<td>0.02</td>
<td>16</td>
</tr>
<tr>
<td>E02A</td>
<td>0.86</td>
<td>0.02</td>
<td>16</td>
</tr>
<tr>
<td>E02B</td>
<td>0.71</td>
<td>0.02</td>
<td>16</td>
</tr>
</tbody>
</table>
This is explained in terms of the implantation depths of the probes. In trees RG2 (Figure 5-3(b)) and RG4 (Figure 5-3(c)), the probes are reasonably well placed through the sapwood, and hence give reasonably good agreement between the two methods (ratios of 0.91 and 0.75). With trees RG1 (Figure 5-3(a)) and RG5 (Figure 5-3(d)) this is not the case (ratios of 0.68 and 0.30). The innermost sensor in RG1 is too close to the point of maximum sap velocity hence sap flux is overestimated when this velocity is allocated to the inner annulus. In tree RG5 the outermost sensor is also situated close to the point of maximum sap flow and therefore allocates too great a velocity to the outer annulus. This is compounded further since errors in sap velocity determination near the cambium result in the greatest errors in sap flux estimation (because of the dependence of sapwood area on tree radius).
Conclusions

The velocity area method is more conservative than the weighted average technique in estimating sap fluxes and is less sensitive to sensor position in the sapwood. For this reason the velocity area method has been selected as the preferred method for this study. Like the weighted average technique it is easily incorporated into a spreadsheet analysis.
# 6 Transpiration patterns of the Lake Albacutya provenance along a saline gradient

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Introduction

The aim of this experiment was to investigate seasonal transpiration patterns along a saline gradient in terms of the relative proportions of rain-derived soil water and groundwater used. In addition, the salt and watertable dynamics in the soil profile at sites under the influence of trees were compared to similar sites where there were no trees. An overview and key findings of this, the largest of three experiments, are presented in the following sections, beginning firstly with the determination of transpiration relative to potential evaporation and rainfall. Differentiating the sources of transpired water between rain and groundwater is discussed next followed by an investigation of the differences between the three sites in the plantation and those outside.

Part 1a. Determination of transpiration relative to potential evaporation

Due to the eventual failure of one of the probes in tree RG3, daily transpiration values along the saline gradient were determined for four trees rather than for all five as originally intended. Figure 6-1 shows the average daily values for each tree for all the logging periods from August 1996 to August 1997. The gaps represent periods when either a logger or its battery failed. Potential evaporation is magnified by a factor of 50 (purely for convenience) in order to observe more easily the relative behaviour of transpiration and evaporation over time.
Figure 6-1: Average daily transpiration along a saline gradient compared to potential evaporation (PE). Salinity increases from RG1 to RG5.

At this macro scale, a number of spatial and temporal responses are evident. Firstly, there is an obvious gradient in transpiration along the transect, away from the edge of the saline lake. Tree RG5 transpired very little relative to the other trees, probably due to the influence of salinity. Tree RG1 on the other hand transpired significantly more than all the others but this was most likely due to its significantly greater size, an advantage of being at the edge of the plantation. Over the 12 month period, changes in transpiration of all four trees in general appeared to reflect changes in potential evaporation.

In order to compare these spatial and temporal differences in water use by the trees, it is necessary to apply scaling factors. At any point in time transpiration can be compared among trees using sapwood area as a scalar. Figure 6-2 shows how strong the linear relationship is between transpiration and sapwood area at all times of the year and would suggest that differences in transpiration are due purely to differences in physical size as related to sapwood area.
Figure 6-2: Relationship between average daily tree water use and sapwood area for four seasons

However, because of the very small sapwood area of tree RG5 compared to the others, the effect at this tree is masked. For six logging periods representing different climatic conditions over the 12 months the daily transpiration rate per unit sapwood area was calculated and is shown in Figure 6-3. Error bars indicate the standard errors and show that significant differences may exist among the transpiration rates (note that there was no replication however).

Figure 6-3: Average daily water use per unit sapwood area
In order to compare transpiration rates under different climatic conditions, potential evaporation was used to normalise the data. Figure 6-4 shows that although there appears to be some positive relationship between transpiration rates and potential evaporation, the degree of correlation for all four trees is not strong ($R^2 = 0.66-0.69$).

![Figure 6-4: Response of transpiration to potential evaporation](image)

This may be because of the effect of the variability of the diffusion driven element of transpiration (i.e. wind speed, canopy conductance, vpd). If the differences are due solely to wind speed and/or vpd, the responses should be consistent among the trees due to the open nature of the plantation. Figure 6-5 shows that the responses do not appear consistent, although all four trees exhibit the same general trends in water use patterns. For all four trees transpiration increases with potential evaporation from September to November but then continues to increase despite a drop in average potential evaporation to mid January. This would suggest that whole plant conductance is increasing during spring, allowing greater transpiration rates to occur. It seems likely that this increase in conductance is due to increased root activity, either as new root growth or reactivation of existing roots. After reaching a peak, transpiration then decreases with potential evaporation through autumn and into winter, resulting in similar rates to the previous winter.
Figure 6-5: Responses of standardised transpiration rates of red gums to potential evaporation along a saline gradient for the period August 96 - August 97
Part 1b. Determination of total annual transpiration relative to annual rainfall

Rainfall was logged automatically from a tipping bucket rain gauge on a daily basis. A total of 403mm fell during the duration of the fieldwork between August 1996 and August 1997. Figure 6-6 shows the distribution and magnitude of rainfall events.

Figure 6-6: Distribution and magnitude of rainfall events at the Minlaton site between 17 August 1996 and 14 August 1997. Note the large summer events.

Transpiration rates were normalised to ground area using the grid spacing of the plantation (9m²) for trees RG2, RG3, RG4 and RG5. For tree RG1, which was on the edge of the plantation, an area of 27m² (based on the average ratio of sap flows between RG1 and RG2 being a factor of three) was estimated. Annual transpiration and proportion of recorded rainfall is shown for trees RG1, RG2, RG4 and RG5 in Table 6-1 for the periods in between each sampling time. It can be seen that trees RG1, RG2 and RG4 transpired approximately the equivalent of rainfall during the spring and winter periods but substantially more during summer and autumn (up to 4.2 times rainfall). This raises the question of the origin of the water being transpired...
in excess of rainfall. Determining the source of water being used by the trees is the subject of part 2 of this chapter.

<table>
<thead>
<tr>
<th>Period</th>
<th>6/9/96 to 23/10/96</th>
<th>24/10/96 to 6/3/97</th>
<th>7/3/97 to 22/5/97</th>
<th>23/5/97 to 14/8/97</th>
</tr>
</thead>
<tbody>
<tr>
<td>P (mm)</td>
<td>84</td>
<td>138</td>
<td>51</td>
<td>130</td>
</tr>
<tr>
<td>T (mm)</td>
<td>T/P</td>
<td>T (mm)</td>
<td>T/P</td>
<td>T (mm)</td>
</tr>
<tr>
<td>RG1</td>
<td>98</td>
<td>1.2</td>
<td>580</td>
<td>4.2</td>
</tr>
<tr>
<td>RG2</td>
<td>94</td>
<td>1.1</td>
<td>465</td>
<td>3.4</td>
</tr>
<tr>
<td>RG4</td>
<td>94</td>
<td>1.1</td>
<td>317</td>
<td>2.3</td>
</tr>
<tr>
<td>RG5</td>
<td>4</td>
<td>0.05</td>
<td>18</td>
<td>0.13</td>
</tr>
</tbody>
</table>

Table 6-1: Transpiration (T) converted to a per unit area basis and shown as a proportion of rainfall (P) for the four periods in between soil samplings.
Part 1c. *Intra and inter-provenance variability in transpiration patterns of E. camaldulensis.*

**Intra-provenance variability (Lake Albacutya)**

The aim of this experiment was to investigate the variability in tree water use of the Lake Albacutya provenance among contours perpendicular to the salinity gradient. Sap flow sensors were installed to monitor transpiration of six trees in row 2 and two each in rows 3, 4 and 5 for the period 17/10/96 to 11/11/96. Failure of one of the loggers in row 3 meant that comparisons could only be made for three of the contours (rows 2, 4 and 5).

Before assessing the variability of water use, a check was made to verify the relationship between water use and sapwood area for this particular time period. Figure 6-7 shows that, amongst the Lake Albacutya provenance trees monitored (including additional trees in rows 1 and 6), there is strong correlation ($R^2 = 0.94$) between average daily water use and sapwood area.

![Figure 6-7: Relationship between average daily water use and sapwood area for 13 Lake Albacutya provenance red gums for the period 17/10/96 to 11/11/96](image)

Furthermore, if the trees in the first three rows (i.e. those most distant from the edge of the saline lake) are considered in isolation to those in rows 5 and 6 (closest to the lake edge), the correlation becomes even stronger for both groups (Figure 6-8: $R^2 = 0.98$ and 0.95). This is as expected where an effect due to salinity is apparent (although it is acknowledged that an increase in $R^2$ does not necessarily indicate an increase in the significance of correlation when the number of degrees of freedom has been reduced).
Figure 6-8: Relationship between tree water use and sapwood area of L. Alba cutya provenance red gums (O) in rows 1-3 and (▲) in rows 5-6.

Sap flows, normalised by sapwood area, were measured in a number of trees for a three week period in spring 1996 as previously mentioned. Generally, sap flows were significantly higher in row 2, furthest from the edge of the saline lake, compared to row 4, where in turn the sap flows were significantly higher than in rows 5 and 6, closest to the saline lake. A typical pattern of daily sap flows over this period is shown for 21 September (Figure 6-9: Average). The error bars represent the standard error of mean. Note however that the sap flows measured in rows 5 and 6 appear to be at the threshold of reliable measurement as far as the equipment is concerned.

Figure 6-9: Average normalised sap flow for trees at different contours (Row 2; n=4, Row 4; n=2 and Rows 5-6; n=3) on 21 September 1996. Error bars represent standard error of mean.
Figure 6-10 shows daily transpiration rates of the six trees in row 2, normalised against sapwood area, and plotted against the average recorded transpiration rate of all the trees for each day. Although the plot appears highly scattered, all the values straddle the 1:1 line (representing 100% correlation) but lie within an area bounded by lines representing values of +/-40% of the 1:1 value. The minimum expected error of tree water use estimation using the heat pulse velocity technique is about 38% [Hatton and others 1995]. Since it was impossible to replicate the experiment within each row, it is not statistically sound to claim significant differences in sap flow within the rows. However, based on the potential error limits calculated previously by [Hatton and others 1995], it is intuitively likely that no differences in tree water use exist along row two.

Similarly for rows four and five, the plots of daily water use against average rate for the row shown in Figure 6-11 and Figure 6-12 lie within the envelope of +/-40% of the 1:1 value (with only a few exceptions for row 5). This again suggests intuitively that no differences in transpiration per unit sapwood area can be inferred along these rows.

Figure 6-10: Comparison of daily water use values of 6 trees in row 2 relative to average water use (X-axis). Note that all values lie within the region bounded by the dotted lines indicating +/- 40% 1:1 value.
Inter-provenance variability (Lake Albacutya and Erudina)

The aim of this experiment was to investigate how transpiration rates of Lake Albacutya and Erudina provenances vary along a saline gradient. Trees from each of the Lake Albacutya and Erudina provenances along contour rows 3, 4 and 6 were instrumented with the sap flow sensors, but failure of both the loggers in row 3 resulted in data being retrieved from only two rows.

Sap flows in the two remaining Erudina provenance trees (M4.10.90 in row 4 and M6.10 in row 6) were measured simultaneously with the Lake Albacutya trees over the same period. The relative daily patterns were very similar, so the sap flow for 21

Figure 6-11: Comparison of daily water use values of 2 trees in row 4 relative to average water use (X-axis). Note that all values lie within the region bounded by lines indicating +/- 40% 1:1 value.

Figure 6-12: Comparison of daily water use values of 2 trees in row 5 relative to average water use (X-axis). Note that most values lie within the region bounded by lines indicating +/- 40% 1:1 value.
September is shown again as being typical, this time including the Erudina provenance trees (Figure 6-13). The Erudina tree in row 4 generally showed greater water use than the average of the two L.Albacutya trees in that row (but see later) whereas the Erudina tree in row 6 showed similar use to its counterpart. As mentioned before, however, measurement in row 6 was probably at the threshold of equipment accuracy.

Figure 6-13: Comparison of sap fluxes of Erudina provenance trees in row 4 (M4.10.90) and row 6 (M6.10) with Lake Albacutya provenance trees in rows 2, 4 and 6 on 21 September 1996.

Figure 6-14 shows that, apart from on one day, all normalised transpiration values of the Erudina provenance tree (M4.10.90) fell within the +/-40% envelope of the Lake Albacutya provenance trees (M4.2 and M4.10). This suggests that significant differences between the water use of the two provenances most likely do not exist.
Figure 6-14: Comparison of daily water use values of Erudina provenance (tree M4.10.90) and Lake Albacutya provenance (trees M4.2 and M4.11) in row 4 relative to average water use (X-axis). Note that most values lie within the region bounded by lines indicating +/- 40% 1:1 value.

For row six, closest to the edge of the saline lake, normalised daily water use values of the Erudina provenance (tree M6.10) are shown plotted directly against those of the Lake Albacutya provenance (tree M6.2) in Figure 6-15. The points are well scattered with several lying outside the +/-40% envelope, indicating poor correlation between the two provenances at this contour, (due to the difficulty in measuring such low flows).

Figure 6-15: Comparison of daily water use of Erudina provenance (tree M6.10) and Lake Albacutya provenance (tree M6.2) in row 6.
Conclusions from Parts 1a, 1b and 1c.

- Transpiration rates, normalised to account for differences in physical size, vary according to tree position along the saline gradient, but not in a linear fashion as might be expected. There appears to be a threshold point along the saline gradient, (between trees RG4 and RG5) above which normalised transpiration is unaffected by salinity. Below this point, there seems to be a dramatic drop in normalised transpiration and only slightly further down the gradient (within 6m), the trees are unable to survive (red gums at least);

- Normalised transpiration rates vary over time in response to changes in potential evaporation but not uniformly. There seems to be a lag in early spring when transpiration is low compared to periods in autumn when similar climatic conditions prevail. This highlights the effect of temporal changes of plant conductance on transpiration, probably due to dynamic changes in root activity;

- Transpiration was up to 2.8, 3.5 and 4.2 times the measured rainfall in summer and autumn for trees RG4, RG2 and RG1 (furthest upslope from saline lake) respectively and approximately equal to rainfall at other times of the year. For tree RG5 (downslope tree, closest to saline lake) transpiration varied between 0.02 and 0.13 times rainfall;

- Significant differences in normalised water use were found among trees upslope (row 2), midslope (row 4) and downslope (rows 5 and 6) along a saline gradient;

- It is likely that no differences in normalised water use exist among the Lake Albacutya provenance trees in the absence of a saline gradient;

- It is likely but not conclusive that no differences in normalised water use between the Lake Albacutya and Erudina provenances exist at a distance of 28m from the edge of the lake. At 22m, differences cannot be ruled out, although absolute flux values at this distance are very small (5-6 L/day) and appear to be at the threshold of accurate measurement by the equipment.
Part 2. Determination of the source or sources of uptake water

This section presents the soil water potential and deuterium analyses for each of the five sampling periods. For each sampling the first row of charts (a-c) show soil matric potential and total soil water potential, as the sum of soil matric and osmotic potential, for each of the three sites along the saline gradient. Note that the X axis in each case is reversed to account for the fact that potential is in reality negative and the natural log is used to account for the fact that potential varies over several orders of magnitude. Extraction of water by the tree roots is therefore most likely where the total potential is closest to zero. The second row of charts (d-f) shows the deuterium content (relative to SMOW) of the groundwater, the soil profile increments and the twig samples of the trees associated with the particular site (trees RG1 and RG2 are associated with site R1, RG3 and RG4 with site R2 and RG5 with R3). Twig sample deuterium contents are indicated by a tree symbol located at the appropriate point on the X-axis. The lengths of the tree symbols are different purely to show at what depth twig deuterium values roughly correspond to soil values.
Sampling 1. 31.7.96

- Surface soil water sourced by trees (Figure 6-16)

Total (●), osmotic (x) and matric (□) potential (natural log kPa)

(a) Site R1  
(b) Site R2  
(c) Site R3

Delta D values (%) for soil, groundwater and twigs

(d) Site R1  
(e) Site R2  
(f) Site R3

Figure 6-16: Sampling 1 - 31/7/96 (a), (b) and (c) soil water potential (kPa) and (d), (e) and (f) delta D relative to SMOW (%) for soil water extracts ●, groundwater ■ and twigs (represented by tree symbols located at the appropriate points on the X axis). Y-axis is depth (cm) in each case.

At site R1 the total soil water potential (TSWP) was dominated by the osmotic component and was greatest at 5cm and 45cm suggesting these as likely extraction depths. The twig deuterium value for RG1 is close to soil at depth 15cm and indicated that the majority of extraction was from near the surface. For RG2 the twig deuterium value was near depth 25cm, midway between 5 and 45cm indicating extraction from both depths was possible.

The TSWP profile at site R2 was similar to that at R1, i.e. greatest near the surface, suggesting that extraction should be close to the surface. Deuterium values were not conclusive for RG4 though, indicating possible extraction from both near the surface.
and from deeper in the profile. The value for RG3 was beyond that of the soil values, indicating either that the soil surface deuterium level had recently been depleted following a rain event, or enrichment due to evaporation had occurred in the twig sample. The latter could have occurred if the twigs were sampled too close to the leaves or if significant amounts of recent rainwater had been retained in the bark.

A similar situation appears for the twig sample from RG5 at site R3 but here the soil deuterium value at the surface was more negative than the next increment, suggesting that rainfall had depleted the surface deuterium content and the tree was in fact using water from the surface soil. The TSWP profile supports this, suggesting that extraction should occur only near the surface due to the continuously decreasing potential with depth.
Sampling 2, 23.10.96

- The dry spring resulted in trees extracting water from lower down the profile, tending towards groundwater (Figure 6-17)

*Total (♦), osmotic (x) and matric (□) potential (natural log kPa)*

(a) Site R1  
(b) Site R2  
(c) Site R3

![Graphs showing soil water potential](image)

*Delta D values (%) for soil, groundwater and twigs*

(d) Site R1  
(e) Site R2  
(f) Site R3

![Graphs showing delta D values](image)

**Figure 6-17**: Sampling 2 - 23/10/96 (a), (b) and (c) soil water potential (kPa) and (d), (e) and (f) delta D relative to SMOW (%) for soil water extracts ♦, groundwater □ and twigs (represented by tree symbols located at the appropriate points on the X axis). Y-axis is depth (cm) in each case.

At site R1 the top 10cm had dried out (i.e. the TSWP is dominated by the matric component) but the profile below this was dominated by the osmotic component. The greatest (least negative) potential was at the base of the profile suggesting extraction should occur only from 45 - 55cm. Deuterium values confirmed this, indicating that tree RG1 was extracting from 55cm and RG2 from around 50cm.
At site R2 surface soils were drier than at R1 (as shown by the higher matric potential) and the greatest potentials were at around 20-40 cm. Deuterium values indicated that RG3 was extracting from 35 cm and RG4 from 45 cm.

At site R3 the surface soils were drier still and the TSWP profile suggests that extraction should occur from 20-40 cm. The deuterium value for RG5 tends to agree, indicating extraction from 35-45 cm.
Sampling 3. 6.3.97

- Trees continued to source water from deep in the profile. TSWP was dominated by matric potential in the upper profile and osmotic in the lower profile (Figure 6-18)

**Total (●), osmotic (x) and matric (□) potential (natural log kPa)**

(a) Site R1  
(b) Site R2  
(c) Site R3

**Delta D values (%) for soil, groundwater and twigs**

(d) Site R1  
(e) Site R2  
(f) Site R3

**Figure 6-18:** Sampling 3 - 6/3/97 (a), (b) and (c) soil water potential (kPa) and (d), (e) and (f) delta D relative to SMOW (%) for soil water extracts ●, groundwater ■ and twigs (represented by tree symbols located at the appropriate points on the X axis). Y-axis is depth (cm) in each case.

At site R1 continued drying of the profile and associated salt accumulation in the upper profile (higher osmotic potential than in sampling 2) suggests that extraction would continue from deep in the profile. The greatest drying effect was apparent at around 55cm, where the matric potential exceeded the osmotic component. This suggests recent extraction from this depth. Deuterium values support this, indicating that both RG1 and RG2 were extracting from a depth of about 60cm.
At site R2, as for site R1, total potential was dominated by osmotic potential except at the surface and lowest at 65cm, suggesting that extraction should be at lower depths than in spring. Deuterium values support this with the value for RG3 coinciding with soil depth 45cm and that of RG4 with 50cm (compared with 35cm and 45cm for sampling 2).

Drying of the profile was greater for site R3 where the TSWP profile suggests extraction from a greater depth than for spring. The deuterium value for RG5 however does not support this, but instead suggests extraction from higher in the profile. This does not seem likely and may indicate poor sampling of the twigs from this tree on this occasion. Suitable twigs were always difficult to locate due to the sparse canopy and it is possible that very fresh wood was sampled where enrichment of deuterium may have occurred due to evaporation (Mensforth, 1996).
Sampling 4. 22.5.97

- Onset of rain allowed trees to switch the source of uptake water. TSWP was dominated by osmotic potential in the upper profile (Figure 6-19)

Total (●), osmotic (✓) and matric (□) potential (natural log kPa)

(a) Site R1  
(b) Site R2  
(c) Site R3

Delta D values (%o) for soil, groundwater and twigs

(d) Site R1  
(e) Site R2  
(f) Site R3

Figure 6-19: Sampling 4 - 22/5/97 (a), (b) and (c) soil water potential (kPa) and (d), (e) and (f) delta D relative to SMOW (‰) for soil water extracts ●, groundwater □ and twigs (represented by tree symbols located at the appropriate points on the X axis). Y-axis is depth (cm) in each case.

The first substantial rains over the last three weeks percolated to about 35cm at site R1, increasing the potentials in the upper profile. The TSWPs suggest that extraction could occur near the surface as well as deep in the profile. Deuterium values indicated that there was still major extraction from around 60cm though for both RG1 and RG2. We note however that there could be time delays between the soil wetting up and water arriving at the twigs, and also associated with the reactivation or growth of roots after summer.
At site R2 percolation only reached to about 15cm, judging by the reversal of the direction of the matric potential curve. This suggests that if the trees had not yet “sensed” surface water then extraction would continue from lower in the profile. For RG3 the deuterium value indicated that this is so but for RG4 the value lies midway between that of the surface soil and the previous extraction depth (50cm), indicating that this tree was in fact in the process of switching over to the surface source.

Percolation of rain water to about 35cm is the same for site R3 as for R1 and the increasing surface soil potentials greater than those from deeper in the profile suggests that a switch from water deep in the profile to nearer the surface may have occurred. As for tree RG4, the deuterium value for RG5 lies midway between that of the surface soil and deep soil suggesting a mixture of source uptake waters.
Sampling 5. 14.8.97

- Trees had most likely switched to the surface soil moisture source (Figure 6-20).

*Total (♦), osmotic (x) and matric (□) potential (natural log kPa)*

(a) Site R1  
(b) Site R2  
(c) Site R3

\[
\begin{align*}
\Delta D \text{ values (‰)} & \text{ for soil, groundwater and twigs} \\
(d) \text{ Site R1} & \\
(e) \text{ Site R2} & \\
(f) \text{ Site R3}
\end{align*}
\]

Figure 6-20: Sampling 5 - 14/8/97 (a), (b) and (c) soil water potential (kPa) and (d), (e) and (f) delta D relative to SMOW (‰) for soil water extracts ♦, groundwater ■ and twigs (represented by tree symbols located at the appropriate points on the X axis). Y-axis is depth (cm) in each case.

At site R1 percolation of rainwater to 55cm with consequent leaching of salt to 65cm resulted in high potentials throughout most of the profile. There was also evidence of drying out of the surface soil following a very dry July. Together this suggests that extraction should have occurred from 15-45cm. The deuterium plots were complex due to the mixing of recent intense rain with existing soil water in which deuterium levels had probably been enriched due to evaporation. The deuterium value for RG1 corresponded with soil values for three depths and that of RG2 for two depths so these are conceivably a combination of values from a number of points.
The profile at site R2 was by now fully wetted but high salt concentrations (possibly due to lateral leaching from upslope) resulted in the greatest potentials at the surface. The deuterium values, although not corresponding directly with any specific soil values, were closest to those of the upper profile and thus tend to confirm extraction from the surface soil.

The profile at site R3 was also fully wetted but the salt front appeared to be lower in the profile than at R2, suggesting extraction was possible from the top 30cm. Similarly to site R2, the deuterium value of RG5, although not corresponding directly with any soil values, again was closest to those of the upper profile and tends to confirm extraction from near the surface.

**Conclusions from Part 2.**

- Deuterium profiles suggest that water is sourced from different depths within the soil profile in response to seasonally varying total soil water potentials at both extremes of the saline gradient.

- Deuterium profiles indicate that the trees are accessing water with similar signatures to that of the groundwater and the lower soil profiles. Therefore the trees are most likely using groundwater through capillary rise and appear capable of doing this for up to half the year (October to May), when transpiration is very much in excess of rainfall.
Part 3. Comparison of the salt and groundwater dynamics under the plantation and under a nearby cleared area

In order to more clearly understand both the effect of salinity on transpiration and the effect of trees on watertables and soil salinity, soil sampling and groundwater monitoring was carried out within the plantation, and some 80m around the saline lake in a cleared area outside the influence of any trees. On each of the five occasions, soil profiles were sampled at points as close as practicable to each of the three piezometers inside and outside of the plantation and along the same contours. At the same time the water table depth was measured in each piezometer and a sample of groundwater taken to measure conductivity.

In the first section the soil matric and osmotic potential profiles are examined for each pair of sites at each sampling period. This is followed by an analysis of the salt accumulation in the soil and in the last section the groundwater depth and salinity levels are presented.
Soil matric and osmotic profiles

Sampling 1. 31.7.96

Soil matric potential (natural log kPa) (plantation ▲, cleared area □)

(a) upslope  
(b) midslope  
(c) downslope

Soil osmotic potential (natural log kPa) (plantation ▲, cleared area □)

(d) upslope  
(e) midslope  
(f) downslope

Figure 6-21: Sampling 1 - 31.7.96 Soil matric and osmotic potential profiles (a),(d) upslope R1 (▲), C1 (□), (b),(e) midslope R2 (▲), C2 (□), (c),(f) downslope R3 (▲), C3 (□)

At the time of the first sampling, similar matric potential profiles existed for all three pairs of sites, typical for winter where adequate rains have wetted the profile (Figure 6-21). The osmotic profiles showed a greater build-up of salt below the surface at the plantation sites compared to the cleared areas, presumably due to water extraction by the tree roots.
Sampling 2. 23.10.96

Soil matric potential (natural log kPa) (plantation ▲, cleared area □)

(a) upslope  
(b) midslope  
(c) downslope

Soil osmotic potential (natural log kPa) (plantation ▲, cleared area □)

(d) upslope  
(e) midslope  
(f) downslope

Figure 6-22: Sampling 2 - 23.10.96 Soil matric and osmotic potential profiles (a),(d) upslope R1 (▲), C1 (□), (b),(e) midslope R2 (▲), C2 (□), (c),(f) downslope R3 (▲), C3 (□)

Surface soils were drier at all sites by spring (Figure 6-22 a-c), particularly at R3 and C3 where there was less cover. The upper profiles at R1 and R2 were drier relative to those at C1 and C2, again presumably because of water extraction by the tree roots. Salt continued to build up in the upper profile at site R1 relative to C1 but more so in the lower profile at R2 relative to C3, whereas at R3 and C3 continued leaching reduced salt levels below the surface (Figure 6-22 d-f).
Figure 6-23: Sampling 3 - 6.3.97 Soil matric and osmotic potential profiles (a),(d) upslope R1 (▲), C1 (□), (b),(e) midslope R2 (▲), C2 (□), (c),(f) downslope R3 (▲), C3 (□)

By the end of summer, all the profiles were very dry, particularly in the top 25cm (Figure 6-23 a-c). At site R2, however, the profile dried out to a lesser extent than at C2, most likely due to greater soil shading. The same scenario would be expected at sites R1 and C1 but this was probably offset by the higher extraction rate by the trees at R1 compared to those at R2. Salt build up was most significant over this period but levels were still highest within the plantation (Figure 6-23 d-f). Substantial rain in late February leached the surface soils to some degree, as evidenced by reversal of the osmotic potential profile curves near the soil surface.
Sampling 4. 22.5.97

**Soil matric potential (natural log kPa) (plantation ▲, cleared area □)**

- (a) upslope
- (b) midslope
- (c) downslope

**Soil osmotic potential (natural log kPa) (plantation ▲, cleared area □)**

- (d) upslope
- (e) midslope
- (f) downslope

Figure 6-24: Sampling 4 - 22.5.97 Soil matric and osmotic potential profiles (a),(d) upslope R1 (▲), C1 (□), (b),(e) midslope R2 (▲), C2 (□), (c),(f) downslope R3 (▲), C3 (□)

After the first substantial rains in early April surface soils were wetted at all sites with associated decreases in salt levels (Figure 6-24 a-f). The lower profile in the cleared area was still relatively dry compared to the plantation however, probably due to higher soil evaporation outside of the plantation.
Sampling 5. 14.8.97

Soil matric potential (natural log kPa) (plantation ▲, cleared area □)

(a) upslope

(b) midslope

(c) downslope

Soil osmotic potential (natural log kPa) (plantation ▲, cleared area □)

(d) upslope

(e) midslope

(f) downslope

Figure 6-25: Sampling 5 - 14.8.97 Soil matric and osmotic potential profiles (a),(d) upslope R1 (▲), C1 (□), (b),(e) midslope R2 (▲), C2 (□), (c),(f) downslope R3 (▲), C3 (□)

By winter 1997, the upper profile outside the plantation was wetter than that inside but the lower profile was in fact drier (Figure 6-25 a-c). At R1, and to a lesser extent at R2, the surface soils were perhaps drying out again due to root extraction. Higher up the gradient (at R1 and C1), significant leaching of salt dramatically reduced the osmotic potential but at R2, R3 and C3 the reduction was only near the surface (Figure 6-25 d-f). A likely explanation of this is the lateral flow of water down the gradient, flushing salt from the higher sites to the lower.
Salt accumulation and lateral leaching

Based on the areal transpiration rates in Table 6-1 and the electrical conductivity of the soil water at the extraction depths suggested by the isotope and soil water potential studies, it is possible to calculate the mass accumulation of salt at each site in the plantation for each of the periods between sampling dates. The mass of salt accumulated may be calculated as the volume of transpiration per unit ground area (L/m²) multiplied by the average salinity of the water (mg/L) at the inferred depth of extraction. EC of soil water was calculated earlier from EC₁₀ readings in the laboratory and has a linear relationship with total dissolved solids (TDS) as shown in Equation 6-1 (Shainberg and Oster 1978).

\[ TDS\ (mg/L) = 640 \times EC\ (dS/m) \]

Equation 6-1

Over the summer period (23/10/96 to 6/3/97) the salt accumulation rates at each site due to transpiration are shown in Table 6-2

<table>
<thead>
<tr>
<th>Site ID</th>
<th>Calculated salt accumulation due to transpiration (g/m²)</th>
<th>Change in salt mass measured (g/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>R1</td>
<td>8313</td>
<td>69</td>
</tr>
<tr>
<td>R2</td>
<td>12838</td>
<td>211</td>
</tr>
<tr>
<td>R3</td>
<td>209</td>
<td>308</td>
</tr>
</tbody>
</table>

Table 6-2: Comparison of calculated salt accumulation due to transpiration and evaporation with the change in salt mass measured at the 3 sites along the saline gradients for the period 23/10/96 to 6/3/97.

This shows that the massive salt accumulation expected due to high transpiration rates of high EC water at sites R1 and R2 did not eventuate and the measured increases in salt mass over this period were in fact two orders of magnitude smaller. In contrast, the increase in salt mass at site R3, where transpiration was very small, was greater
than that expected due to transpiration. Evidently there was some process which removed the salt, since there was no significant build up in the root zones. A possible mechanism to explain this is lateral leaching along the top of the clay layer. Up slope of the plantation a lupin crop was grown during the winter of 1996 and this was left as stubble after harvesting. There would have been no transpiration therefore and since there were five significant rainfall events (>15mm: see Figure 6-6) over the summer period, substantial infiltration through the sandy surface to the clay layer could have occurred. With high transpiration rates occurring in the plantation, this would have created a potential head difference by which lateral flow would be driven. Using simple Darcy flow calculations it can be shown that to remove, say, the 8kg of salt that would have accumulated at site R1, such that the average TDS remains fairly constant at 15g/L, and assuming that the bottom 10cm of the sand layer is saturated with a hydraulic conductivity of around 10cm/hr (Hillel 1971), requires an average potential head gradient of only 1.7cm per metre. It is quite conceivable then that a sufficient potential head difference could develop across the zone of influence of the plantation (approximately 21m) and so leach the accumulated salt from the root zone. For the other periods of the year when transpiration was lower relative to rainfall, the required gradient would have been even lower.

Below the cleared area, outside of the plantation, the lower transpiration rates due to the presence of sparse tall wheat grass and the absence of trees would have resulted in minimal salt accumulation in the root zone and a barely significant potential head gradient across the transect of piezometers C1 to C3. Salt accumulation at the surface due to evaporation from the soil, and downward leaching by rainfall however would have resulted in greater vertical rather than lateral movement of salt.

The differences in salt and water dynamics between the plantation and the cleared area should be reflected in the behaviour of the respective local groundwater tables. Under the cleared area (piezometers C1, C2 and C3) it would be expected that groundwater salinity should vary in response to surface evaporation and downward leaching of salt following rainfall. However, under the plantation (piezometers R1, R2 and R3), groundwater salinity would remain fairly constant over time since accumulated salt
would be removed by lateral leaching to some distance beyond the piezometers. Here, it would be subject to the same processes as for the cleared area i.e. surface evaporation and downward leaching. Leaching of salt to the groundwater downslope however would have limited effect on the groundwater salinity immediately under the plantation since movement of salt would be by the much slower process of diffusion. Groundwater depth would still respond to regional recharge rates however and the relative differences between the plantation and the cleared area should remain reasonably constant.

The depth and salinity of the groundwater was monitored under the plantation and the cleared area between September 1996 and August 1997. The following section presents the results of the monitoring at each of the five major sampling occasions.

**Groundwater depth and salinity**

Water table was lower under the plantation relative to the cleared area and showed a slight drawdown effect under piezometer R1, most likely due to extraction by tree roots of RG1 or RG2. A strong salinity gradient existed under the cleared area but salinity was much greater under the plantation.

Figure 6-26: Groundwater depth and salinity under plantation (piezometers R1, R2, R3 - solid line) and under cleared area (piezometers C1, C2, C3 - dotted line) 6.9.96
The water table under the plantation was still lower than under the cleared area, which also exhibited some drawdown effect at C1. There was still a strong salinity gradient outside the plantation but near the lake salinity at C3 approached that of R3.

Figure 6-27: Groundwater depth and salinity under plantation (piezometers R1, R2, R3 - solid line) and under cleared area (piezometers C1, C2, C3 - dotted line) 23.10.96

Both water tables continued to drop, with that outside the plantation by now closer to that under the plantation. Salinity at C2 was now closer to that of R2 as the cleared area salinity continued to approach that under the plantation.

Figure 6-28: Groundwater depth and salinity under plantation (piezometers R1, R2, R3 - solid line) and under cleared area (piezometers C1, C2, C3 - dotted line) 6.3.97
Despite the onset of the first rains, water tables were now at their lowest and the salinity under the plantation was exceeded by that under the cleared area.

Figure 6-29: Groundwater depth and salinity under plantation (piezometers R1, R2, R3 - solid line) and under cleared area (piezometers C1, C2, C3 - dotted line) 22.5.97

Substantial rains in early August raised water table levels, more so outside the plantation. Salinity levels were very similar still but under the cleared area there was a greater decrease of salinity, probably due to greater direct recharge (the trees still transpired the equivalent of rainfall during this period).

Figure 6-30: Groundwater depth and salinity under plantation (piezometers R1, R2, R3 - solid line) and under cleared area (piezometers C1, C2, C3 - dotted line) 14.8.97
Conclusions from Part 3.

- Drying out of the upper profile (as shown by higher soil matric potentials) occurred at a higher rate in the plantation than in the cleared area in spring, probably due to extraction by tree roots;

- Salt build up (higher soil osmotic potential) was greater under the plantation than under the cleared area especially during summer and autumn (due to higher transpiration rates);

- Lateral leaching of salt under the plantation from the upslope site (R1) occurred following substantial rain;

- Water tables under the plantation were consistently lower than under the cleared area but salinity levels varied, being higher in all seasons except summer when salinity under the cleared area was marginally higher;

- Increases in water table levels and corresponding decreases in salinity levels were greater, in general, outside the plantation.
Proposed mechanism explaining salt and water dynamics under the plantation - the apparent cycling of salt

It has been shown that the four trees upslope from the saline lake transpired in excess of four times the measured rainfall (per unit area) for the period of late spring 1996 through to the end of autumn 1997 yet there was no evidence of salt being accumulated in the root zone during this time. In addition, the salinity of the groundwater under the plantation did not change significantly over the same period compared to that under a nearby cleared area. This raises the question of what may have happened to the substantial quantities of salt that should have been left behind. From simple Darcy flux calculations it is concluded that lateral leaching would be sufficient to remove salt out from under the trees and deposit it downslope, where some would re-enter the groundwater by vertical leaching during winter. This would explain not only how the trees managed to continue transpiring apparently saline groundwater but also why the salinity of the groundwater immediately below the plantation remained static.

The proposed mechanism controlling these processes is outlined in Figure 6-31
Figure 6-31: Proposed mechanism of lateral leaching that prevents salt accumulation under the plantation. Rainfall (1) on the stubble upslope from the plantation infiltrates the sandy upper soil layer until it reaches the much less permeable clay layer. A small proportion (2) infiltrates the clay layer and recharges the groundwater. A larger proportion (3) moves laterally along the top of the clay layer due to a potential head gradient caused by transpiration rates in the plantation (4) in excess of 4 times rainfall compared to zero in the stubble upslope. Salt accumulated from capillary rise of groundwater (5) under the plantation as a result of tree transpiration is leached laterally (6) some distance downslope where the potential head gradient declines. Evaporation from surface soil (7) in summer deposits the leached salts, a proportion of which is leached downward (8) to the watertable in wetter months. Very slow diffusion of salt back under the plantation (9) presumably occurs.
In contrast, Figure 6-32 shows that the processes in force under the cleared area were much simpler. Net recharge (a) upslope of the piezometers did not translate into a high enough potential head gradient down which significant lateral leaching could occur. Net discharge of groundwater (b) due to high evaporation in the hotter months exceeding downward leaching in winter resulted in a net increase in accumulated salt in the upper profile and corresponding fluctuations in groundwater salinity.

Figure 6-32: Typical water and salt balance following the removal of trees: (a) net recharge area where salt is not accumulated in the root zone and (b) net discharge area where salt is accumulated in the root zone in hot, dry months and leached to the water table in cooler, wetter months but with an overall net salt gain.
7  Edge effects on transpiration due to advection of wind energy

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Introduction

Under uniform climatic conditions it is expected that trees of the same species will transpire similar volumes of water per unit sapwood area. Trees at the edge of a plantation or interception belt, however, may behave differently due to greater advection of wind energy. Significant differences in transpiration rates would have implications for the design of interception belts, so the aim of this, the final experiment, was to compare transpiration patterns of trees at the edge of a *Eucalyptus globulus* plantation with those away from the edge, over a period of varying climatic conditions.

Transpiration measurement

Sixteen sap flow dataloggers were installed initially, but due to the distance of the site from Adelaide it was only possible to monitor their performances once (17th December) during the experiment. Inspection of the loggers at this time showed that only 14 had been operating and that only nine could be used subsequently due to battery limitations. Effectively, this divided the experiment into two monitoring periods. For the first period (5-16 December 1996) 14 of the 16 loggers were functioning, including all four on the edge trees but for the second period (17 December 1996 to 2 January 1997) only nine were working including only two on the western edge. These problems were due to a combination of battery failures and inexperience with the earlier types of loggers.

Figure 7-1 shows a strong linear relationship between daily sap flux and sapwood area for the first logging period. Correlation for all trees (edge and inner) is high but is higher still for the edge trees in isolation, suggesting that there is potentially an edge effect. For the second logging period (18 December 1996 to 2 January 1997) the loggers on the two eastern edge trees failed leaving only the two on the western edge so it is not possible to show correlation for the edge trees in isolation for this period. However, correlation between daily sap flux and sapwood area is again very high for this period as is shown in Figure 7-2.
Chapter 7 - Experiment 3 - Results and Preliminary Discussion

Figure 7-1: Relationship between average daily water use and sapwood area of 4 edge trees (open symbols) and 10 inner trees (solid symbols) for the period 5-16 December 96. Correlation for all trees (dotted line) is high ($R^2 = 0.92$) but is higher still ($R^2 = 0.97$) for just the edge trees (solid line).

Figure 7-2: Relationship between average daily water use and sapwood area of 2 edge trees (open symbols) and 7 inner trees (solid symbols) for the period 18 December 1996 to 2 January 1997. Correlation is very high ($R^2 = 0.97$).

Measurement of climatic factors and calculation of potential evaporation

At 15 minute intervals from 5 December 1996 to 2 January 1997, average temperature, relative humidity, solar radiation, wind speed and wind direction were logged at the top of a 15m high tower situated on the western edge of the plantation. Estimates of potential evaporation were made for each 15 minute period using the Priestley-Taylor equation. This assumes that potential evaporation can be represented
universally as being proportional to the equilibrium evaporation rate as shown in Equation 7-1;

\[ PE_{P-T} = \alpha \frac{s \Phi_n}{\lambda(s + \gamma)} \]

Equation 7-1

where \( \alpha \) = Priestley-Taylor coefficient (assumed = 1.26 in this case),

\( s \) = the slope of the saturated vapour density versus temperature curve,

\( \gamma \) = the psychrometric parameter,

\( \lambda \) = latent heat of vaporisation,

and \( \Phi_n \) = net solar radiation, which can be calculated as per Equation 7-2;

\[ \Phi_n = \Phi_g(1 - \alpha) + Q_l \]

Equation 7-2

where \( \Phi_g \) = global short wave radiation (logged parameter)

\( \alpha \) = albedo

and \( Q_l \) = net long wave radiation i.e. (atmospheric \( Q_a \) - terrestrial \( Q_t \)) * N

where \( N \) = sunshine hours.

Atmospheric and terrestrial long wave radiation (in watts) can be estimated by assuming soil and atmospheric temperature are the same as air temperature as follows (Equation 7-3 and Equation 7-4)
\[ Q_a = 5.31 \times 10^{-13} \times T_k^6 \]

Equation 7-3

and \[ Q_t = 0.95 \times 5.67 \times 10^{-8} \times T_k^4 \]

Equation 7-4

where \( T_k \) = air temperature in degrees K.

The terms \( s, \gamma, \) and \( \lambda \) are all temperature dependent and can be interpolated from tables of compiled values e.g. Thornley and Johnson (1990). Daily values of potential evaporation were calculated as the sum of all 15 minute averages for each day and are shown in Figure 7-3. Note that these values of PE are not intended to represent maximum transpiration from the plantation but merely to allow comparison of transpiration rates between days (i.e. the relative values of PE rather than the absolute values).

![Figure 7-3: Daily potential evaporation over the logging periods as calculated by the Priestley-Taylor equation.](image-url)
For the first period (5-16 December), PE varied widely from less than 3mm/d on 6 December to greater than 7mm on only three days. In contrast, the second period (18 December - 2 January) was dominated by hotter drier conditions with PE in excess of 7mm on 11 of the 17 days. No rain fell in the first period and only 2mm towards the end of the second period.

![Figure 7-4: Relationships between daily sap flux per unit sapwood area and potential evaporation for edge trees (square symbols) and inner trees (triangular symbols) for the period 5-12 December 1996 (solid symbols) and period 17 December 1996 - 2 January 1997 (open symbols).](image)

Figure 7-4 shows the relationships between normalised sap flux and potential evaporation (PE) as calculated from the Priestley-Taylor equation for both logging periods. Second order polynomials were used to indicate lines of best fit (since the relationships are obviously non-linear, though an initially sloping line tending to the horizontal with increasing PE would be more realistic). In both the edge and inner trees normalised sap flux increased with PE initially and then became independent (constant) as PE increased. The plots suggest that minor (though always significant) differences in normalised sap flux existed at low PE but these differences became greater at higher PE.
To investigate these differences, values of normalised sap fluxes for edge and inner trees were plotted against each other for each day (Figure 7-5). Edge effects can be assumed to be negligible if the ratio of the two fluxes is constant (i.e. the correlation is high) and equal to unity, since this implies identical responses. If the ratio is constant but not equal to unity, this implies an edge effect which will most likely be a competitive effect due to proportional differences in canopy conductance between the edge trees and the inner trees, (indicating different levels of water availability for example).

Figure 7-5: Relationship between normalised tree water use of edge trees and inner trees for (a) period 1 (5-17 December 1996) where line of best fit $y=1.64x$ ($R^2 =0.82$) and (b) period 2 (18 December 1996 - 2 January 1997) where line of best fit $y=1.52x$ ($R^2 =0.81$). Error bars represent standard errors of mean.

Figure 7-5 indicates reasonable correlation between edge and inner trees in both periods ($R^2 = 0.80-0.81$), suggesting a high degree of proportionality (but note that the slopes of the two plots differ markedly from unity (1.64 and 1.52), indicating likely differences in canopy conductance, an analysis of which follows). This implies that water availability is likely to be partially responsible for the differences (note that no rain fell in period 1 and only 2mm were recorded towards the end of period 2).
Calculating actual and critical canopy conductances

Canopy conductance can be estimated using an inverse form of the Penman-Monteith equation (Granier and others 1990) with the evaporation term (E) being replaced by tree transpiration per unit ground area. The area of ground “occupied” by each tree is not easily quantifiable but it is reasonable to assume that the occupied area will be proportional to the cross-sectional sapwood area (sensu Hatton and Wu (1995) who postulated that individual trees tend towards an equilibrium between their size and domain). For each of the inner trees, this can be calculated by multiplying the plantation grid spacing (9m²) by the ratio of actual sapwood area to average sapwood area of all the inner trees. The area “occupied” by the edge trees is more uncertain since the plantation grid spacing does not apply. An effective grid spacing can be calculated however, by comparing the average sapwood area of the edge trees with that of the inner trees and multiplying this by the actual grid spacing. The ratio of edge tree to inner tree sapwood area was found to be about two so the effective grid spacing for the edge trees was assumed to be 18m². The area “occupied” by each of the edge trees was then calculated as for the inner trees by multiplying the effective grid spacing by the ratio of actual sapwood area to edge tree average sapwood area.

Average daily canopy conductance (mm/s) for each tree was then calculated. Note that inverting the Penman-Monteith equation may be achieved in a number of ways but, where vapour density deficit is used, can always be simplified to the following (Equation 7-5);

\[
g_c = \frac{E}{c_1 - c_2 E}
\]

Equation 7-5

where

\[
c_1 = \frac{s\Phi_N}{\lambda\gamma g_a} + \Delta\rho_{va} \quad \text{and} \quad c_2 = \frac{s + \gamma}{\gamma g_a}
\]
Transpiration may respond to increasing wind speed (through its effect on aerodynamic or boundary layer conductance $g_a$) in one of three ways, depending on the relative values of $g_a$ and canopy conductance. A critical value of canopy conductance exists such that, when canopy conductance is above this value, transpiration increases (is enhanced) with increasing wind speed and decreases (is suppressed) when it is below. If canopy conductance is at this critical value, transpiration is independent of wind speed. By rearranging the Penman-Monteith equation and setting evaporation to be independent of aerodynamic conductance, the critical value of canopy conductance can be calculated as follows (Thornley and Johnson 1990; equation 14.6e) (Equation 7-6);

$$g_c(critical) = \frac{s \Phi_N}{\lambda \Delta \rho_{va} (s + \gamma)}$$

Equation 7-6

By calculating average daily values for critical canopy conductance and comparing these to average canopy conductances calculated for individual trees, it is possible to identify days where transpiration is likely to be enhanced and days when it is likely to be suppressed by increasing wind speed. Table 7-1 summarises the critical canopy conductances for each day and the calculated average canopy conductances for each tree for each day.
Chapter 7 - Experiment 3 - Results and Preliminary Discussion

Table 7-1: Calculated average daily canopy conductances (mm/s) for all sampled trees in period 1. Values in bold type indicate days when calculated canopy conductances exceeded the critical canopy conductance that is shown in the right hand column.

<table>
<thead>
<tr>
<th>Date</th>
<th>Edge trees</th>
<th>Inner trees</th>
<th>Critical g_c</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>W01A W01B</td>
<td>E01A E01B</td>
<td>W02B W05 W09 W13 E16 E09 E02A E02B</td>
</tr>
<tr>
<td>5-Dec</td>
<td>4.6 3.9 3.6</td>
<td>4.8</td>
<td>1.7 1.1 1.8 2.5 1.6 3.1 3.5 2.0 2.5 2.5</td>
</tr>
<tr>
<td>6-Dec</td>
<td>0.9 0.9 0.8 1.1</td>
<td>0.3 0.2 0.4 0.7 0.3 0.8 1.0 0.5 0.8 0.6</td>
<td>1.6</td>
</tr>
<tr>
<td>7-Dec</td>
<td>2.8 2.6 2.3 3.0</td>
<td>1.0 0.8 1.3 1.9 1.4 2.3 2.5 1.6 1.9 2.0</td>
<td>4.6</td>
</tr>
<tr>
<td>8-Dec</td>
<td>1.9 1.8 1.8 2.2</td>
<td>0.7 0.6 0.9 1.5 1.0 1.6 2.0 1.2 1.4 1.5</td>
<td>2.9</td>
</tr>
<tr>
<td>9-Dec</td>
<td>3.5 3.5 3.1 4.1</td>
<td>1.5 1.1 1.7 2.6 1.8</td>
<td>3.0 3.2 2.0</td>
</tr>
<tr>
<td>10-Dec</td>
<td>3.0 2.8 2.5 3.0</td>
<td>1.1 0.8 1.4 2.0 1.5</td>
<td>2.4 2.6 1.6 1.8 1.9</td>
</tr>
<tr>
<td>11-Dec</td>
<td>4.7 4.1 3.9 5.0</td>
<td>1.9 1.3 1.8 3.0 2.1 3.3 3.8 2.4 2.5 2.7</td>
<td>4.6</td>
</tr>
<tr>
<td>12-Dec</td>
<td>3.1 2.7 2.6 3.2</td>
<td>1.1 0.8 1.2 2.0 1.3 2.1 2.6 1.6 1.7 1.8</td>
<td>4.4</td>
</tr>
<tr>
<td>13-Dec</td>
<td>3.9 3.4 3.6 4.5</td>
<td>1.5 1.0 1.4 2.4 1.6 2.8 3.3 1.9 2.5 2.1</td>
<td>3.8</td>
</tr>
<tr>
<td>14-Dec</td>
<td>3.2 2.9 3.0 3.7</td>
<td>1.1 0.8 1.4 2.2 1.3 2.4 2.7 1.8 1.9 1.9</td>
<td>2.1</td>
</tr>
<tr>
<td>15-Dec</td>
<td>5.4 4.8 4.5 5.2</td>
<td>1.9 1.5 2.0 3.2 2.2</td>
<td>3.5 4.1 2.7 3.2 2.6</td>
</tr>
<tr>
<td>16-Dec</td>
<td>1.8 1.7 1.6 2.1</td>
<td>0.6 0.6 0.8 1.4 1.5 1.7 1.8 1.1 1.4 1.2</td>
<td>2.2</td>
</tr>
</tbody>
</table>

It can be seen from this table that enhancement of transpiration was most likely on 15 December, when the critical canopy conductance was exceeded by all the edge trees and six out of the ten inner trees. Conversely, it can be seen that enhancement was unlikely on six days, when none of the conductances exceeded the critical value.

Taking this further, it is then possible to rank the days in order of the likelihood of critical conductance being exceeded. If it is measurable, the enhancement of transpiration of edge trees with respect to inner trees will be most apparent on the days when there is the highest likelihood of the critical conductance being exceeded. On the days when there is less likelihood of the critical conductance being exceeded, either there should be no edge effect apparent or, in extreme conditions, transpiration of the edge trees may be suppressed with respect to the inner trees.

Figure 7-6 shows that, in period 1, for the four days when canopy conductances were least likely to exceed the critical value, a strong linear relationship existed between normalised water use of the four edge trees and normalised water use of the four inner trees whose conductances never exceeded the critical value. For the other days, when edge tree canopy conductances were more likely to be greater than the critical value, the relationship was still linear (though not as strongly so), but the slope of the line was steeper, indicating greater transpiration of the edge trees with respect to the inner trees. This is evidence for enhancement of transpiration of the edge trees.
In the second period, there was only one day when canopy conductance exceeded the critical value, so it is to be expected that the transpiration of the edge trees would not be enhanced with respect to the inner trees. However, as mentioned previously, it may be suppressed. Figure 7-7 shows that, for the six days of highest likelihood of the critical conductance being exceeded, the relationship between edge and inner tree normalised water use was good ($R^2 = 0.89$), as it was for the three days of least likelihood ($R^2 = 0.95$), but the slope of the line was lower in the latter case, indicating probable suppression of edge tree transpiration. The error bars in this figure have been omitted since they are large and show no significant differences but despite this the correlation is high and the downward trend is in agreement with the theory.
Conclusions

Plots of tree water use against sapwood area indicate that sapwood area is a suitable scaler for comparing water use between trees ($R^2 = 0.92$).

Edge trees showed higher normalised sap fluxes (i.e. greater water use per unit sapwood area) compared to inner trees (defined as trees in all rows other than the eastern and western edge rows) particularly as PE increased. These differences in normalised water use between the edge trees and the inner trees can be explained in the main by the differences in canopy conductance, probably as a result of better access to water in the case of the edge trees.

In addition, wind effects were significant in enhancing transpiration of edge trees with respect to inner trees by approximately 10% on days when canopy conductance was sufficiently higher than a critical value. It is likely that this figure could be higher for well-watered conditions. The original assumption that the soil profile would have been well-watered appears to have been invalid. There was also an indication that edge tree transpiration was suppressed on days of very low canopy conductance, although differences were not significant.

On the basis of these findings it is clear that edge trees will transpire at a higher rate than inner trees as competition for water develops and that this may be further enhanced by advection of wind energy. Interception belt design will therefore tend to favour wide tree spacing with only 2 or 3 rows to optimise growth of sapwood and leaf area, thus maintaining high canopy conductance values and to maximise the access of wind.
Chapter 8 - General Discussion

8 General Discussion

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Introduction

The main aim of this project was to establish whether or not interception belts can be expected to transpire sufficient volumes of water to be considered a feasible option for controlling rising groundwater. To address this the first three experiments set out in chapter 4 were designed to determine how much water red gums transpired at different points along a saline gradient, how this varied over the course of the seasons and what proportion of transpired water was in fact groundwater. The final experiment set out to determine if edge trees would transpire significantly more than trees away from the edge because of the advective effect of wind.

With regard to the dimensions of interception belts and their placement in saline landscapes, the main issues which need to be discussed are the spatial and temporal influences of salinity on tree water use patterns, how transpiration is partitioned between groundwater and rain-derived soil water and how such systems can remain sustainable. The optimal configuration or spacing of trees in belts is governed by the maximum attainable ratio of transpiration to sapwood area per unit land area. This ratio will be dependent upon the degree of enhancement (or depression) of transpiration by the advection of wind energy and will also vary over time as tree canopies develop. In the remainder of the chapter, these issues are discussed in the light of the results presented in chapters 6 and 7. Finally, implications for the design and placement of interception belts are discussed.

Transpiration patterns along a saline gradient

Tree position along the saline gradient had a significant effect on transpirational ability but this was not due entirely to salinity itself. The tree furthest from the edge of the saline lake (RG1) transpired at a much higher rate compared to the other trees because it was physically larger. When transpiration was normalised to sapwood area, rates were comparable among trees RG1, RG2 and RG4 relative to RG5 (although see later regarding intra-provenance variability). The tree closest to the edge of the lake (RG5) transpired at the lowest rate both in absolute terms and also when normalised to sapwood area.
The behaviour of the trees suggests that those trees upslope of row 5 are above a critical threshold position, which allows them to transpire freely. Tree RG5 appears to be below this threshold and its transpiration and growth are thus limited. In the plantation as a whole, very few trees of this species exist below this position and those that do are severely stunted relative to other trees. This implies that the plantation was ineffective below this critical point but it is not possible to predict a critical upslope position because the greatest growth and transpiration was found in the highest trees. Had the plantation been extended further upslope, it would be expected that at some point the trees would have been unable to access the groundwater and this would have been reflected in lesser growth rates. Positioning of belts in the landscape will therefore be restricted to zones where groundwater access is not limited and salt export exceeds salt import.

Transpiration in response to PE

Over time transpiration rates varied in response to potential evaporation. From winter into spring they increased with increasing PE and from summer through to autumn, decreased with decreasing PE. Between the end of spring and the middle of summer, however, there was generally an increase in water use but a decrease in potential evaporation. This hysteresis effect shows that plant responses to atmospheric driving forces were not consistent since climatic conditions in spring did not produce the same transpirational responses for similar conditions in autumn. The likely explanation for this is that whole plant conductance changes seasonally as root activity changes, resulting in differing ability of the trees to extract and transpire water. At the start of spring, roots were extracting water from near the surface, where total soil potentials were least negative. As the upper profile dried out, roots lower in the profile became more active, facilitating greater extraction. Transpiration rates increased during spring presumably while root growth, and thus whole plant conductance, was still increasing. Transpiration effectively lagged behind PE while the roots were growing. Continued root growth into early summer would have allowed transpiration rates to continue increasing even though maximum potential evaporation rates occurred in late spring. Maximum transpiration rates occurred in mid summer (January 1997), then declined as potential evaporation declined through
late summer and autumn. A steeper decline in transpiration with respect to PE occurred in late autumn, corresponding with a changing over to surface soil water extraction by the roots following the break of season. The final transpiration rates measured in winter 1997 corresponded to rates measured during the first logging period in winter 1996, thus completing the hysteretic loop.

Predicting likely water use of interception belts relative to potential evaporation will be difficult without some foreknowledge of the root system dynamics. Where extraction of water is not from constant or uniform depths in the soil profile it can be expected that there will be a varying response of transpiration to atmospheric demand.

**Transpiration relative to rainfall**

Providing that excess rainfall is able to reach the tree roots and that it will be intercepted and transpired when it does so, it is then possible to calculate required areas of revegetation. The proportion of land that must be planted to trees to obtain zero net recharge is equal to the ratio of the estimated recharge under the agricultural land to the estimated discharge by the trees. Since climatic conditions vary seasonally, it is useful to quantify recharge and discharge relative to rainfall. The rate at which interception belts transpire in excess of rainfall can be used as a direct measure of the degree of recharge control possible.

During spring, transpiration normalised to ground area “occupied” by each tree was approximately equal to the rainfall of that period for all but the smallest tree (RG5). In summer, transpiration ranged from 4.2 times the amount of rainfall for tree RG1, to 3.4 times for RG2 and 2.3 times for RG4. Similar patterns were evident in autumn, with transpiration to rainfall ratios ranging from 4.2 (RG1) to 2.8 (RG4). Winter ratios were similar to values for spring for these three trees. In contrast, the smallest tree, closest to the saline lake (RG5) transpired very little relative to rainfall (0.02 to 0.13). Over a full year, in which 403mm was recorded at the Minlaton site, the ratio of transpiration to rainfall was about 2.5 upslope, 2.2 and 1.6 midslope and 0.1 downslope. In a study of the water use patterns of two 9 year old red gum provenance plantations on a discharge site at Wubin in Western Australia, Marshall and others (1997) reported overall transpiration rates of about 2.7 times rainfall (1148mm
transpired to 432mm rainfall), with transpiration matching rainfall in the wetter months.

As might be expected, there will be an upper limit to annual transpiration, since it is constrained by responses to climatic and physiological variables. Therefore the relationship between transpiration and rainfall will not hold in high rainfall zones. Kelliher and others (1993), in a review of evaporation and canopy characteristics of coniferous forests and grasslands, reported maximum hourly evaporation rates of 0.46mm/hr, which translated to only 4.0mm/day. Maximum surface conductances for a range of woody species are remarkably consistent at around 20mm/s (Kelliher and others 1995) and this in turn places an upper limit on transpiration, as determined by climatic variables and not limited by soil moisture availability.

Given this upper limit, the ratio of annual transpiration to rainfall may be used as a means for estimating the areas of interception belts necessary to mop up excess recharge. The most conservative (i.e. greatest) estimate of belt area requirements will follow from the assumption that 100% of rainfall upslope of the belt recharges the groundwater. In reality this will not be the case since transpiration from annual crops will occur during the growing season and evaporation from the bare soil or stubble will occur at other times. Kennett-Smith and others (1996), from previous studies, assumed that one twelfth of rainfall that fell in the Upper South East region of South Australia recharged groundwater in unwooded areas where groundwater was greater than 1m deep. In areas of shallow groundwater they assumed that all rainfall in unwooded areas recharged groundwater. Based on these figures an interception belt would prevent recharge over an area 30 times its own area (2.5 divided by 1/12), again assuming that water is supplied to the belt at a sufficient rate and is of adequate quality.

**Transpiration variability within and between provenances**

Within the Lake Albacutya provenance, significant differences were found among water use (normalised to sapwood area) of three rows of trees at discrete contours along the saline gradient. Among trees within rows, although it was not possible to
show statistically, no apparent differences in normalised transpiration could be inferred.

Transpiration rates between the Lake Albacutya and Erudina provenances were compared and again, although it could not be shown statistically, it was inferred that differences did not exist. Note however that comparisons were only made in rows four and six due to equipment failure and only one tree of the Erudina provenance was available for sampling in each row, making replication impossible. The study by Marshall and others (1997), in contrast, showed that significant differences did exist between clones of the two provenances that they investigated and that such information could be used to better match species with landscape conditions for remediation work.

When the aim is to maximise transpiration, subtle differences in growth and survival between provenances at the extreme end of the salinity gradient may be unimportant. The selection of sites with a high gradient of lateral flow to ensure salt export would be the preferable option.

*Partitioning of available water sources*

The success of interception belts will depend on their ability to continue transpiring at peak levels particularly through periods of extreme atmospheric demand. Naturally, this will necessitate the use of groundwater, either directly or by capillary rise or as a mixture with rain water. Determining how available water sources are partitioned is thus an important process in the investigation of tree water use patterns.

This study showed that at three sites along the saline gradient trees sourced water from different depths within the soil profile in response to changing soil water potential. In winter 1996, when significant rains had raised matric potentials to near maximum values and leached accumulated salts, extraction of water by the tree roots was from near the surface. As the surface soils dried by transpiration and direct evaporation, extraction occurred from lower in the profile, where potentials were higher. By the end of summer, extraction was at the deepest levels and deuterium analysis indicated that the water being transpired had the same isotopic signature as
the groundwater. This pattern continued into autumn, when surface soil potentials began to increase to high enough levels to exceed deeper profile levels. By winter 1997, deuterium analysis again indicated that extraction was from surface soils.

The deuterium analyses indicated that tree water was sourced from deep in the soil profile for the hotter half of the year, since isotopic signatures of twig xylem water were similar to that of the groundwater during these times. It is logical that the trees were accessing an alternative source at this time since the heat pulse velocity studies showed that transpiration rates were far in excess of rainfall during summer and autumn. A study by Thorburn and others (1993) reported groundwater usage for *E.camaldulensis* on the Chowilla floodplain ranging from 58% in winter to 100% in summer. Even trees with access to permanent stream water used groundwater to a large extent (Mensforth and others 1994; Thorburn and Walker 1994). Similar isotopic studies by Dawson (1996) on the water use of sugar maple trees indicated that small trees, which used surface soil moisture for most of the year were able to extract a small proportion of groundwater during dry periods whereas large trees used groundwater almost exclusively.

*Sustainability in terms of salt and water dynamics*

For interception belts to be useful in the long term, peak levels of transpiration must be sustainable. This implies that not only must a supply of water be accessible to meet demand but it must also be extractable by the tree roots. The process of root extraction excludes salt in most species, which means that, unless there is some mechanism in place to remove the salt, its inevitable accumulation will lower the osmotic potential of the soil water in the vicinity of the roots to levels which are too negative. Unchecked, the natural outcome of this is a reduced ability of the trees to transpire and ultimately, plant mortality. For salt to be leached from the root zone there must be periodic flows of water either downwards following rain or along lateral gradients. Lateral gradients may occur along the interface of soils of different hydraulic conductivities (e.g. in duplex soils where the infiltration rate through the sandy upper horizons is significantly greater than through the underlying clay and can result in temporary, perched water tables). Gradients may also exist where shallow
groundwater moves between net recharge and net discharge zones. Obviously, transpiration will be sustainable when the rate of salt removal exceeds the rate of salt accumulation but peak rates will only be maintainable when leaching is sufficiently high or frequent enough during periods of high atmospheric demand (e.g. following unseasonably high summer rainfall events).

Under the plantation at the Minlaton site, there was a greater build up of salt compared to the cleared site during summer and autumn when transpiration exceeded rainfall and in spring when transpiration and rainfall were roughly equal. Leaching of salt from the profile was sufficient however to maintain high transpiration rates upslope but at the same time, salinity levels in the groundwater below the trees did not increase, indicating that salt was being removed laterally. Under the cleared area, groundwater salinity increased over summer, indicating that leaching occurred in more of a vertical direction than laterally. The inference that can be drawn from this is that the gradient of groundwater flow under the plantation was sufficient enough to transport salt far enough away from the root zone whereas under the cleared area the gradient was less steep. The greater transpiration rates of the plantation were such that the drawdown effect resulted in a steeper gradient of groundwater flow relative to the cleared area. The implication of this then is that, by strategically incorporating a belt of trees into the landscape, an area of land which was previously a net groundwater recharge zone is converted into a net discharge zone but with the added bonus of being a net exporter of salt. In the long term this means that although salt is being deposited downslope, the reduction in recharge possible through enhanced transpiration from the interception belts will lead to lower water tables under the discharge zones, creating greater depth for increased natural leaching by rainfall.

*Edge effects due to the advection of wind*

Optimum configurations of interception belts need to be determined if maximum water use is to be attained. Depending on the influence of wind, configurations may be either dense plantings, which have high numbers of stems per unit ground area or wide spaced, staggered rows which have fewer stems but larger trees with fuller canopies, yielding similar leaf and sapwood areas per unit ground area. Enhancement
of transpiration by wind energy will favour more open plantings whereas dense plantings would be preferred where transpiration is depressed by increasing wind speed.

Results from the experiment conducted at the blue gum plantation at Talinga in the south east of South Australia showed that when soil moisture was not limiting, edge tree transpiration was enhanced relative to inner plantation trees by the effect of wind. When soil moisture became limiting, no enhancement of transpiration was detected and in fact there was evidence to suggest that transpiration was being depressed. Since interception belts are intended to be used on sites where soil moisture is generally not limiting, then design should favour wide spaced configurations to facilitate the access of wind energy to all the canopies of the belt.

The experiment highlighted the importance of a critical value of canopy conductance, above which transpiration would be enhanced by increasing wind speed and below which it would be depressed. Maintaining high canopy conductance values would therefore maintain the opportunity for enhanced rather than depressed transpiration. Smith and others (1997) investigated the energy budgets of windbreaks in the Sahel region in the west of Africa and reported enhancement and depression of transpiration relative to equilibrium evaporation (E_{eq}) at different times of the year. During moist periods, when surface conductances were high, up to 60% of transpiration was due to advection and vertical entrainment, and was thus enhanced relative to E_{eq}. In dry periods, surface conductances were reduced due to soil moisture stress and consequently, advection and entrainment were responsible for depression of transpiration to as little as 40% of E_{eq}. This study highlighted the importance of advection in water use studies of narrow belts of trees where equilibration of humidity between the vegetation and the atmosphere does not have time to occur. These same principles will naturally hold true for interception belts, hence it is critical, in order to maximise water use, to allow for advection and the enhancement of transpiration when surface conductance is not reduced by soil moisture stress.
Implementation of interception belts

The practical use of interception belts requires detailed consideration of catchment hydrogeology prior to planting. The area of agricultural land contributing to recharge and some volumetric quantification of that recharge will allow an estimate to be made of the width and density of belts required to counter it. Knowledge of the groundwater surface both spatially and seasonally and of the variability in electrical conductivity is essential for the positioning of interception belts in the landscape.

Location of interception belts in the landscape

The success of interception belts in transpiring at maximum rates will be reliant on their accurate placement in the landscape. Belts placed too low in the landscape i.e. too close to a discharge zone will be at risk of waterlogging and due to the levelling out of the groundwater gradient preventing sufficient lateral leaching (position A in Figure 8-1). In particular this will be the case where high transpiration rates of saline water by the belt upslope lead to the lateral leaching and deposition of large salt loads to the downslope side of the belt. Trees may then become “salted out” and die or at best perform poorly. In contrast belts placed too high in the landscape may not be able to access the groundwater and would therefore be at risk of water stress during the hotter and drier months (position C in Figure 8-1). These trees would then only transpire the equivalent of rainfall at best.

Figure 8-1: Interception belt placement options: A, too low - trees are at risk from waterlogging and salting out; B, above break of slope - trees can access the water table which has a steep gradient; C, too high - trees are unable to access the water table.

Optimal locations therefore will be where; groundwater is shallow enough to be accessible, either directly or via capillary rise; there is a strong groundwater gradient
with high potential for lateral leaching and; the transmissivity of the soil is high enough to permit sufficient lateral flow. The recharge/discharge zone interface has greatest potential to suit these criteria (position B in Figure 8-1). This has been proposed in what is known as “break of slope” planting and some preliminary investigations have been carried out by Clifton and others (1995). Initial results from that work however have indicated that the trees are unable at present to access groundwater, possibly because they are still too young but also because they may be too far up from the break of slope.

**Interception belt dimensions**

The size of interception belts will depend on the size of the recharge zones they are required to operate in and the depth of recharge occurring in those zones (assuming that aquifer transmissivity does not limit lateral flow). Based on belt water use of about 2.5 times rainfall and recharge of 0.1 times rainfall say, then, for a simple two-dimensional case, belt width should be one twenty fifth of the width of the recharge zone width for example. Naturally, in more complex catchments, width of the recharge zone is less easily calculated, but such problems may be overcome using 3-D modelling techniques.

Discharge is dependent on the total amount of leaf area or sapwood area per unit ground area. This can be maximised either by having a high stem number with low individual leaf or sapwood area or a low stem number with high leaf or sapwood area. Ultimately the latter is the preferred option to maximise advection but this may not be realistic initially. Naturally, seedling trees could not perform at maximum required rates, hence it would be preferable to plant at a very high density at first, then thin out as the trees developed. Once the trees were able to access groundwater, further thinning out would allow greater canopy development for each tree, maximising the opportunity for advection and thus enhancement.

On purely economic grounds though, it may be preferable to maintain high stem number per unit land area to maximise pulpwood production. For the Green Triangle Tree Farm Project in south eastern Australia, for instance, a viable plantation area of 20 ha is based on a planting density of at least 1000 stems per hectare (PISA Forestry
undated). The minimum length of ten metre wide (three row) interception belts required therefore to produce 20 ha is 20 km. The implementation of interception belts may be influenced by such minimum requirements.

Conclusions

It was originally hypothesised that interception belts would be useful tools for controlling groundwater levels and therefore managing dryland salinity. It has been shown that strategically placed trees transpired substantially more water than just rainfall and that for half the year this water was of groundwater origin. Because of the strategic location of the trees, at the interface of the recharge and discharge zones, a potential head gradient facilitated the lateral leaching of salt from the root zone and prevented the trees from becoming "salted out". Deposition of the salt downslope prevented the groundwater itself from becoming more saline under the trees. These preliminary findings, although recorded over only one complete season, indicate that interception belts are indeed likely to be useful tools in the management of dryland salinity. The following chapter aims to investigate this further by considering the implementation of such belts in the Upper South East catchment of South Australia, one of five focal catchments for salinity research in Australia (Webb 1994).
Chapter 9 - A Case Study

9 Implementation - A Case Study of the Upper South East of South Australia

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Introduction

As mentioned briefly in Chapter 1, the Upper South East region of South Australia is an important agricultural region for sheep and cattle production. It extends over 6800 km², encompassing more than 400 properties and more than 80% of the land is planted with pastures (Upper South East Dryland Salinity and Flood Management Plan Steering Committee 1993). Over the last 50 years more than 85% of the original vegetation has been cleared, wetlands have been drained and surface water flows have been altered with the installation of numerous drainage schemes. The Upper South East is a closed catchment in that it has no natural outlet for surface water flows. Historically, excess surface water travelled slowly towards the north where it would evaporate in natural salinas. Following the replacement of native vegetation with shallow rooted pastures and the construction of drains, both the volume of excess water and the rate at which this water moves northwards have increased, resulting in the development of salinity and waterlogging problems. A program of revegetation was proposed for the region with the use of interception belts a high priority (Bulman and others 1993). The aim of this chapter is to evaluate the feasibility of implementing interception belts in this region.

Description of the Upper South East

The climate is Mediterranean and average rainfall varies from about 450 mm in the north to 550 mm in the south. Annual pan evaporation varies from 1500 mm in the south to 1700 mm in the north (MacKenzie and Stadter 1992).

The topography of the region is complex, consisting of a series of calcarenite strandline dunes that run roughly north-west. The soils on these dunes are deep and infertile whereas the soils on the interdunal flats tend to be duplex. Groundwater depth fluctuates seasonally, rising to the surface in winter in some lower lying areas such as interdunal flats and landlocked depressions within the dunal ranges. Over a large area of the region the groundwater is less than 2 m deep.
deep. Figure 9-1 shows the depth to groundwater over a portion of the region at the end of summer when levels are lowest.

Figure 9-1: Depth to groundwater levels at the end of summer
(Source: Upper South East Dryland Salinity and Flood Management Plan Steering Committee (1993)
The salinity of the groundwater varies both spatially and temporally, although it is not well recorded. Values ranging from 1500mg/L to greater than 12000mg/L were reported by MacKenzie and Stadter (1992). In winter the groundwater is recharged by rainfall and run on from higher parts of the catchment. Where the groundwater is shallow, high evaporation rates in summer cause the salinity to increase to very high levels (e.g. >60dS/m (Mensforth 1996)). It is these areas which are at risk or are already experiencing dryland salinity.

The degree of salinisation of surface soils has been categorised and the areas of each category reported by Cann and others (1992). The geographic extent of these are depicted in Figure 9-2. Category 1 comprises the higher areas (256,050 ha) which are not saline and not at risk of becoming saline. Areas which are currently not saline but which are at risk of becoming so are included in Category 2 (175,050 ha). Categories 3 (109,540 ha), 4 (75,350 ha) and 5 (65,950 ha) are mainly restricted to the interdunal flats, and described as “mildly to moderately”, “moderately to highly” and “very highly” saline respectively.
Figure 9-2: Soil salinity categories of the Upper South East catchment from Upper South East Dryland Salinity and Flood Management Plan Steering Committee (1993) compiled from Cann and others (1992).
In an investigation into the potential impacts of vegetation based management options in the Upper South East, the effects of manipulating recharge rates and varying the extinction depth for evapotranspiration were modelled by Kennett-Smith and others (1995). One of their key findings was that only an increase in extinction depth of evapotranspiration (i.e. the depth to which plant roots could extract water) could lower water tables under the interdunal flats. Due to extreme waterlogging potential and the saline nature of the groundwater in many areas of the Upper South East, this scenario would appear unrealistic in nature. Mensforth (1996) reported that the bulk of root activity of Melaleuca halmaturorum, one of the most salt tolerant species of the low lying flats, was limited to just the top 60cm of soil.

Other results indicated that a very large reduction in recharge was required to decrease the salinisation rate under the dune ranges but, even if this was achievable, it would be unlikely to significantly reduce the area of potential salinisation of the interdunal flats. However, reducing recharge on the dunal ranges would decrease the salinisation rate under the interdunal flats because of the reduction in discharge. This is because the water tables under the flats are maintained by recharge contributions from the dunal ranges. In time a reduction in recharge would benefit the interdunal flats since the associated reduction in discharge would allow a gradual reduction in salt accumulation, which in turn would allow a gradual rehabilitation of saline areas. The most favourable and feasible option reported was to reduce annual recharge on the dunal ranges to ~2mm, with an extinction depth for evapotranspiration of 2m and to assume that recharge would continue at the rainfall rate on the flats where the extinction depth was restricted to only 1m. The model predicted that, under this scenario, water table levels under the dunes would decline slowly (~25cm over 5 years) but this would lead to the lowest chloride levels on the flats. The following discussion evaluates the feasibility of implementing this scenario (i.e. eliminating recharge through the dunal ranges) with the use of interception belts.
Locations for interception belts in the Upper South East

From the above study by Kennett-Smith and others (1995) a key location for the implementation of interception belts would be the boundaries between recharge and discharge areas along the edges of the dunes. This can be roughly approximated by the boundaries of the green areas in Figure 9-2 i.e. the areas which are neither saline nor at risk of becoming so. Priorities should be to plant along the western or “downstream” edges first since groundwater flow is east to west. Within the dunal ranges themselves, planting around the edges of low lying depressions above the break of slope will assist in the overall reduction of recharge. This can be achieved at the farm scale rather than on a regional basis.

Dimensions for interception belts in the Upper South East

The size of interception belts will depend on the extent and value of groundwater recharge. Annual recharge through the dunal ranges has been estimated at 50-70mm (Walker and others 1992) at sites where the annual rainfall is 530mm. Hydraulic conductivity of the unconfined water table aquifer is high due to the sandy nature of the soils (taken as 68m/d or 283cm/hr by Armstrong and Stadter (1992) and later by Kennett-Smith and others (1996)) and significant groundwater gradients exist across the dunal ranges (MacKenzie and Stadter 1992; Kennett-Smith and others 1994). This implies that salt accumulation should not be a problem under interception belts. Assuming that interception belts can transpire about 2.5 times rainfall (say 1200mm annually) and recharge is conservatively put at 100mm then the area of belts to be planted would need to be one twelfth of the area of the dunal ranges. Conversely if recharge is set at the lower value of 50mm only one twenty fourth of the area would need to be planted. The current estimate of land that is not saline nor at risk is about 256,000 ha. Of this then, between about 10,000 and 20,000 ha would need to be planted to interception belts to eliminate recharge from the dunes. Use of the existing GIS datasets would enable a precise length of the boundary lines to be calculated and from this the necessary width of belts could be determined.
Constraints

Effectiveness of the belts will be subject to their being able to access groundwater at all times without being at risk of waterlogging. Obviously, this further limits the area of potential planting locations but in general, the Category 1 soil salinity areas overlie deep groundwater (> 3m) and those areas exhibiting some degree of salinity (Categories 3, 4, and 5) overlie shallow groundwater (< 2m). More precise planting locations could be determined therefore by combining the depth to groundwater and soil salinity category GIS datasets to produce a dataset which comprises, say, Category 1 or 2 soil salinity with summer groundwater depth between 2m and 3m. This would reduce the risk of planting areas prone to waterlogging or summer drought. Accuracy testing of the resultant GIS dataset would be necessary to establish a reasonable degree of confidence.

One of the major agronomic problems that has become prevalent in the Upper South East has been the development of non-wetting characteristics in the dune sands, which has threatened the re-establishment of perennial pastures in the region (Upper South East Dryland Salinity and Flood Management Plan Steering Committee 1993). If not treated, this will be a problem in the establishment phase of interception belts since the seedling trees will be unable to access groundwater immediately and will therefore be at risk of summer drought.

Landholder adoption may also constrain the effectiveness of the scheme. The optimum planting locations will out of necessity be in areas that are considered productive. Loss of this land to the planting of interception belts may encounter some reluctance on the part of landholders, particularly in the case where the effects of salinity are minimal. Unfortunately the recharge areas which are responsible to a high degree for salinisation often exist away from the areas experiencing the symptoms of salinity. A regional approach, which promotes uniform property planning and financial equity, is thus warranted to ensure a high level of adoption.
Conclusions and further work

In conjunction with other remediation strategies such as recharge zone revegetation with perennial pastures, saltland agronomy and groundwater drainage, interception belts are likely to be a useful tool for dryland salinity management. They have the ability to transpire large volumes of excess water, particularly in the hotter months when atmospheric demand is high and are less likely to encounter resistance to adoption from landholders in comparison to other wholesale revegetation schemes.

Bearing in mind that the Upper South East catchment is very large in comparison to the scale of the interception belts themselves, then some of the parameters (e.g. soil hydraulic conductivity, groundwater depth and salinity) used in the above analysis will by necessity be estimates only. The calculated dimensions and proposed locations for planting are therefore educated guesses but may form the basis for further, more detailed analysis. Further study should be aimed at modelling in some detail the performance of interception belts in finer scale groundwater models (using MODFLOW for instance) as well as in existing regional models (such as described by Kennett-Smith and others (1996)) or more complex ecosystem process models such as WaVES (Hatton and others 1995).


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