Second Australian Stream Management Conference
8-11 February 1999, Adelaide, South Australia

Water Balance of Plantations in Southeastern South Australia

David Sheriff[1] *and Tanya Doody*

SUMMARY: Water resources in southeastern South Australia are stored in aquifers which are partly recharged by local rainfall. Surface stream flow is very uncommon and, with the exception of the Glenelg River on the Victorian - South Australian border, results only from outflow from the aquifer. Stream flow is essentially underground throughout the region. This water resource is valuable for local irrigated agriculture, tourism and secondary industries. There is growing concern about possible negative effects of trees, particularly of forest plantations, on the hydrological balance of the region. In collaboration with the local plantation forest industry and The Forest and Wood Products Research and Development Corporation, research is being undertaken by the CSIRO Forestry and Forest Products Plantation Forest Research Centre near Mount Gambier into water use by *Pinus radiata* stands. Measurements were made on an older stand because its impact of on regional hydrology is likely to be greater than that of younger, smaller trees. Results reported here are from a 23 year old closed - canopy stand, investigating effects of fertiliser and thinning on water use. Results indicate that *P. radiata* has very efficient mechanisms to limit water use during dry periods and that water use (transpiration + evaporation) by a stand is not greater than annual rainfall. Thus, in this study there was not a net use of groundwater by the stand. This is consistent with a study on the same site using naturally occurring stable isotopes of water, where it was deduced that all water in the trees originated from the soil and so the stand did not deplete the aquifer. Transpiration was lower for fertilised trees.

THE MAIN POINTS OF THIS PAPER

- Groundwater in the region is a major resource and the region’s only water resource
- Groundwater use by plantations could threaten their productivity and other users of groundwater: agriculture, manufacturing and tourism
- Measurements on a plantation indicate it extracts water only from the soil profile and does not to not deplete the groundwater
- A fertilised stand grew faster (above ground) but transpired less water than an unfertilised stand
- There were strong linear relationships between tree basal area, sapwood area and foliage area

1. INTRODUCTION

Pinus radiata plantations in southeastern South Australia and western Victoria contribute considerably to Australia's softwood production. Increasing investment by the wood processing industry and consequent demand for wood in the region is anticipated to result in a supply shortfall of about 20% by 2010. Therefore, an increased sustainable productivity is essential to the industry's viability. Further, The Plantation 2020 vision promotes a trebling of the area of land used for production forestry over the next 22 years (DPIE, 1997). It is very important that such a significant change in land use should not have adverse effects either on the sustainability of its use or offsite. Because of greater interception losses, potentially deeper rooting and the perennial habit of the vegetation, the water balance of a forested site may be less positive than that of a dry land agricultural crop or pasture site. The region’s water resources are stored in, and flow through aquifers which are partly recharged vertically from local rainfall. Surface stream flow is very uncommon and, with the exception of the Glenelg River on the Victorian - South Australian border, results only from outflow from the aquifer. Stream flow is essentially underground throughout the region. However, issues of the quantity and quality of water supply in this regional subterranean stream are essentially the same as those related to surface streams in other regions.

In any climatic region productivity of a species is related to water use. Nambiar (1994) and Sheriff (1996) have shown that the productivity of the region's plantations is significantly higher than elsewhere in southern Australia with the same, or greater rainfall (annual potential evaporation is greater than rainfall so, rainfall is a surrogate for water loss). A possible explanation of this greater productivity is the presence throughout the region of good quality groundwater, in an unconfined aquifer, that may be physically accessed by tree roots. This higher productivity could be due to *P. radiata* plantations supplementing rainfall on the site by withdrawing water from the aquifer. The trees’ foliage would be able to maintain a higher diffusive conductance and so gain more photosynthate than if they relied only on current rainfall. If the high productivity depends on water from the aquifer, large water use will deplete the aquifer, and so threaten sustainability of this high productivity, as well as having off-site effects deleterious to other users of the water unless ameliorative management techniques are applied. Such techniques can be developed only if the quantity of

---

[1] CSIRO Forestry and Forest Products. P.O Box 946 Mt Gambier S.A 5290 ph 08 8721 8112 fax 08 8723 9058

water used by plantations is determined. Typically, *P. radiata* plantations are on sites where the aquifer surface is 8 - 20 m below ground surface, with an annual rainfall in the range of 650 - 800 mm.

Potential water use, and so possible use from depth is likely to be positively related to site productivity. Greatest water use from depth will most likely be on sites with larger trees, because these have greater physical potential to access the aquifer, and on sites where productivity is high, ie where foliage area and diffusive conductance of the foliage is large.

To examine these issues a study was undertaken to examine stand transpiration in relation to site water balance and effects of thinning and fertiliser application on this balance and water use from the aquifer; to examine whether stand water use is sustainable.

2. METHODS

2.1 The Site

The site was selected to represent a mid - rotation stand typical of *P. radiata* in the region, with a productivity towards the higher end of the range. The stand was about to undergo thinning and fertilising as part of the normal stand management regime. The soil profile is a podzolised sand A horizon, overlying a dark brown to yellowish brown unstructured light-clay B horizon formed *in situ*, broadly typical of sites used for plantation forestry in the region.

The plantation was 23 years old, about 30 m tall and with an average diameter at breast height (DBH) of 33.9 cm (range 12.5 - 49.7 cm) when it underwent a second thinning and fertiliser application. Several fertiliser and thinning treatments were established (Sheriff 1998). The amounts of water transpired by all treatments that received fertiliser were the same. Similarly, fertilised and unfertilised thinned treatments transpired the same amounts of water as their unthinned counterparts. Therefore, data from only two treatments are presented here. These were a thinned, unfertilised control (N0P0) and a thinned, fertilised treatment, that had received 200 kg/ha elemental nitrogen and 80 kg/ha phosphorus (N200P80). There were three replicate plots of 38 x 38 m of each treatment.

2.2 Measurements

Water use of individual trees was measured with the heat pulse technique (Figure 1) and stand water use was calculated from this by simple scaling, using the techniques of Teskey and Sheriff (1996). It was found that for any tree the average rate of transpiration per leaf area was independent of tree size. Thus, scaling to the stand level is possible if leaf areas of individual trees in the stand are known. For conifer species there is often a linear relationship between tree leaf area and sapwood cross - sectional area at the base of the stem at a site (e.g. Teskey and Sheriff, 1996; Whitehead, 1978; Whitehead *et al.* 1984). This seems to be associated with a linear relationship between the potentials for transpiration from the foliage and for the tree's sapwood to supply the transpired water (Whitehead *et al.* 1984). In a single - aged stand there may also be, for temporal rather than mechanistic reasons, a close, linear relationship between sapwood cross - sectional area and stem basal area, as found by Teskey and Sheriff (1996). When this occurs leaf area can be well - predicted from stem basal area, calculated from DBH. Water use by a tree is then the product of transpiration per unit leaf area and tree leaf area. Stand water use is the sum of water used by all trees.

2.3 Trees

DBH and height were measured annually for each tree.

At the beginning of the experiment six healthy trees, selected to cover a wide range of diameter, were felled. Diameters of all first - order branches were measured and foliage was completely removed from an approximately average sized branch from every other first - order branch whorl. Needle length and projected needle width at three positions along the length of a needle were measured on a subsample of this foliage, using a ruler and microscope, respectively. The main sample and subsample were then oven - dried and the needle area for the sample branch (A_s) calculated as the product of the dry weight of the foliage sampled from the branch and the area of foliage in the subsample divided by the dry weight of the subsample. The area of foliage in a whorl or the whorl above was determined as the product of A_s and the total diameter of branches in the whorl divided by the diameter of the sample branch.

To enable scaling of water use to the stand level relationships were determined between stem basal area, sapwood area and foliage area for each tree, as discussed above. Stand sapwood and foliage areas were determined as the sum of values for all trees in the stand. These values of foliage area obtained at the beginning of the experiment were used to calibrate values of leaf area index (LAI) [LAI = (leaf area) / (ground area)] measured with a LiCor LAI 2000 at this time. Values for the different replicates were sufficiently different that they covered the range of LAIs measured throughout the experiment with the LAI 2000. The calibration function was used to determine true leaf area values from LAI 2000 measurements, made about every 1 - 6 months, most frequently after thinning and fertilising, to determine how leaf areas changed with season and treatment. Daily values of LAI required to calculate leaf conductance and to model transpiration were calculated by interpolation.

2.4 Water use

Sap flux (volume per unit time flowing through sapwood) in individual trees was determined in three replicate plots of each treatment using Greenspan SF300 probes and Greenspan loggers (Figure 1). Measurements showed little radial variation in velocity over the radius of the sapwood, other than a sharp decrease at the physiological heartwood - sapwood boundary and at the sapwood - cambial boundary. The probes attached to each logger were, therefore, positioned radially so that they were at centres of equal sapwood area. Heat pulse values were determined every 30 minutes (48 values per day) and data downloaded to a portable computer every 7 - 14 days. Sap velocities were calculated from the heat pulse data using the methodology provided by Greenspan. Tree sap flux (in l/h/tree) was determined as the product of velocity and conducting area. Summing the 48 values for each day and dividing by two provides a value in l/d/tree, then dividing by tree leaf area gives the rate of transpiration per unit leaf area per day (in $l/m^2/d$). Transpiration per unit leaf area did not vary with tree size (see also Teskey and Sheriff 1996), so an average rate of transpiration per unit leaf area per day was calculated from the three measurements for each treatment. Stem basal areas were calculated from DBH measurements and treatment leaf areas were determined from the relationship between stem basal area and leaf area (see later).

Figure 1: Heat pulse equipment attached to a tree at the site of the experiment.

Treatment transpiration in mm per day (the same as the value in $l/m^2/d$), and dimensionally the same as rainfall, but loss rather than gain, was determined as the product of average daily transpiration and leaf area index.

The treatments discussed in this paper were thinned in 1994 and fertiliser was applied in late spring 1995, so over this interviening period there was, effectively, one treatment: thinned, unfertilised (N0P0). Trees to be used for sap flow measurements were chosen so that their sapwood areas were the stand average and the 90% and 10% confidence intervals above and below this.

2.5 Soil moisture

Soil moisture was determined from neutron probe readings (CPN503DR neutron probe), measured at 30 cm intervals between depths of 30 cm and 270 cm at two positions in each plot of the N0P0 control. These measurements were made approximately every two weeks in the first two years of the experiment and then every four weeks.

2.6 Weather data

Daily values of mean, maximum and minimum relative humidity and temperature, and totals of rainfall, solar radiation and windrun were recorded by an Easidata Mk-3 weather station established in a clear area about 4 km from the experiment site. These data were downloaded to a portable computer every 7 - 14 days. Daily mean values of vapour pressure deficit (VPD) were calculated from recorded values of relative humidity and temperature. Because of the large non - linearities in changes in saturation vapour pressure with temperature, daily values of VPD were determined from calculated maximum and minimum values. Aerodynamic conductance was calculated from wind velocity using the method of Monteith (1965).

2.7 Effects of the environment on transpiration

Potential evaporation from an object depends on the object's radiant energy balance, diffusive conductances between it and the bulk of the atmosphere and the moisture deficit of the air. Transpiration of a leaf, a tree or a stand is also affected by the conductance of the surface, i.e. by the product of leaf area and leaf conductance, as shown by the Penman - Monteith equation (e.g. Rundel and Jarrell 1989). Foliar conductance can be calculated from transpiration and weather data using the same equation. Because atmospheric conductance is large, transpiration is strongly linked to foliar conductance in conifer canopies. In this experiment, the average canopy conductance for each treatment was calculated from tree water use and weather data.

2.8 Apportioning water use

Site water balance was examined by use of a simple model (Sheriff, unpublished) using soil moisture and weather data, the Penman - Monteith equation and responses of leaf conductance to the environment. Soil moisture at the beginning of the measurement period and daily weather data were input. Evaporation, transpiration, soil moisture and drainage were output.

3. RESULTS

3.1 Relationships in the stems and foliage of trees

The linear relationship between stem basal area and foliage area of each tree (Figure 2) is similar to that of Teskey and Sheriff (1996) for a younger (16 year old) *P. radiata* stand.

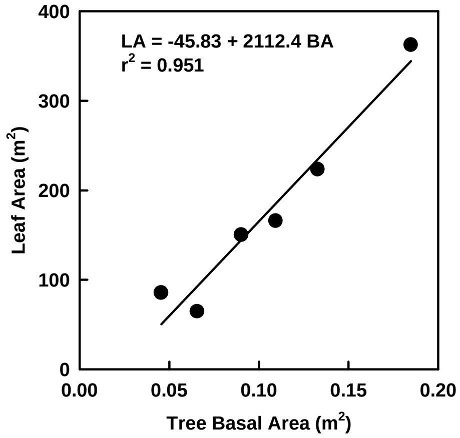

Figure 2. Relationship between leaf area and basal area under bark of the 23 year old *P. radiata* trees.

3.2 Water use

Water use by individual trees was proportional to leaf area, larger trees used more water than smaller trees and sap flow velocities were the same in different sized trees; as observed by Teskey and Sheriff (1996).

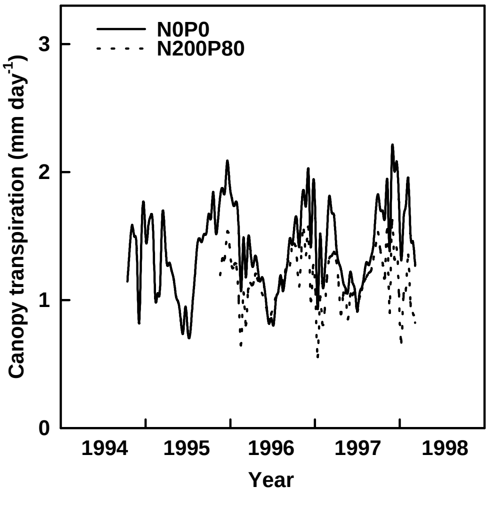

Figure 3. Variation in transpiration over time. Transpiration values have been integrated over ten day periods to reduce noise in the data and more clearly show trends.

Water use by stands (Figure 3) is greatest in spring and early summer, with a second peak often obvious in autumn. Lower water use in summer results from stomatal closure, caused by the dry atmospheric and soil environments. Further analysis of data from this stand indicates this response was dominated by the effect of VPD. Large stomatal responses to vapour deficits have previously been reported for *P. radiata* by Sheriff (1995) and Sheriff and Mattay (1995), as well as for conifers generally (e.g. Whitehead and Jarvis 1981, Roberts 1983). Lower water use in winter results from the low availability of energy to evaporate water at this time.

Rainfall was 828, 834 and 567 mm in 1995, 1996 and 1997, respectively. Transpiration was less than rainfall every year; the difference was smallest in 1997. The unfertilised control stand transpired 500, 504 and 521 mm over this period, while the fertilised stand transpired 343 and 409 mm during 1996 and 1997. Over these two years, transpiration was 73% of rainfall in the control and 54% of rainfall in the fertilised stand, while the stands produced 69 and 86 m^3/ha of stem wood over this period. Thus, 19% less of the water that fell as rain was used to produce 25% more wood in the fertilised, compared to the unfertilised stand. Calculated evaporation was 27 - 33% of annual rainfall.

4. CONCLUSIONS

Generally, because of the way leaf conductance responds to vapour pressure deficit and because transpiration is strongly and positively linked to leaf conductance and vapour pressure deficit in conifers, transpirational water loss was highest in spring - early summer. Transpirational water loss was proportional to leaf area within a treatment and was highest in the unfertilised treatment, where stemwood production and leaf area were smallest. There may have been greater evaporative losses from fertilised stands, but increasing growth by fertilisation does not have a negative effect on the hydrological balance of the site. It may increase runoff, which at this site would be downwards towards the aquifer. Water use efficiency for stemwood growth was greater in fertilised treatments. This could result from: (1) better stomatal control of transpiration; (2) a higher photosynthetic efficiency, resulting in a greater fixation of carbon per unit water lost, which is consistent with gas exchange measurements made on *P. radiata* (e.g. Sheriff *et al.* 1986); (3) a greater partitioning of photosynthate to stemwood production in fertilised trees; or (4) a combination of these factors.

Measurements over a three year period at this site showed no evidence of net water use from the unconfined aquifer. Soil moisture values from the control treatment were consistent with simulated values (not shown). That this stand of large, vigorous *P. radiata* did not use more than current rainfall indicates that such stands do not threaten their own sustainability or have large off - site effects on stored water. This is consistent with an allied study by McEwan and Leaney (1996) at the same site, in which they determined the source of water taken up by the trees by measuring naturally occurring, stable isotopes of hydrogen in water in the aquifer, the soil and tree tissues at several times during the summer. Their results clearly indicate that the trees were removing water only from the soil and not from the aquifer.

Thus, in this study there was not a net use of groundwater by the stand and so the stand did not deplete the aquifer.

The unconfined aquifer is about 18 m from the surface at this site, and further measurements are needed to relate this information to other sites that have groundwater at other depths and that have different soil profiles.

In the Introduction it was mentioned that Nambiar (1994) and Sheriff (1996) have shown that the productivity of the region's plantations is significantly higher than elsewhere in southern Australia with the same, or greater rainfall (water availability is assumed to limit water use). The finding that stands in this experiment had a high growth rate and relied entirely on current rainfall again raises the question of why stands in this region are so productive.

5. REFERENCES

DPIE (1997). Plantations for Australia: The 2020 Vision. Department of Primary Industries and Energy, Canberra, Australia.

McEwan, K and Leaney, F. (1996). Using the natural abundance composition of stable isotopes in Pine trees, groundwater and soil water to estimate groundwater use by pine plantations near Mt. Gambier, South Australia. CSIRO Consultancy Report No. 96-34. CSIRO, Adelaide, Australia.

Monteith, J.L. (1965). Evaporation and environment. Symposium of the Society for Experimental Biology. **19**: 205-234.

Nambiar, E.K.S. (1994). Relationships between water and nutrients in Australian forests: application to wood production and quality. Plant and Soil **168-169**: 427-435.

Roberts, J.M. (1983). Forest transpiration: a conservative hydrological process? Journal of Hydrology **66**: 133-141.

Rundel, P.W. and Jarrell, W.M. (1989). Water in the environment. In Plant Physiological Ecology. Field methods and instrumentation. Eds Pearcy, R.W., Ehleringer, J.R., Mooney, H.A. and Rundel, P.W. pp 29-56. Chapman and Hall, London.

Sheriff, D.W., Nambiar, E.K.S. and Fife, D.N. (1986). Relationships between nutrient status, carbon assimilation and water use efficiency in *Pinus radiata* (D. Don) needles. Tree Physiology **2**: 73-88.

Sheriff, D.W. (1995). Gas exchange of field-grown *Pinus radiata* - relationships with foliar nutrition and water potential, and with climatic variables. Australian Journal of Plant Physiology **22**: 1015-1026.

Sheriff, D.W. (1996). Responses of carbon gain and growth of *Pinus radiata* stands to thinning and fertilizing. Tree Physiology **16**: 527-536.

Sheriff, D.W. (1998). Increased and sustainable production of *Pinus radiata* plantations and its potential impact on groundwater use in the se of South Australia and Western Victoria. Report for Forest and Wood Products Research and Development Corporation.

Sheriff, D.W. and Mattay, J.P. (1995). Simultaneous effects of foliar nitrogen, temperature, and humidity on gas exchange in *Pinus radiata*. Australian Journal of Plant Physiology **22**: 615-626.

Teskey, R.O. and Sheriff, D.W. (1996). Water use by *Pinus radiata* trees in a plantation. Tree Physiology **16**: 273-279.

Whitehead, D. (1978). The estimation of foliage area from sapwood area in scots pine. Forestry **51**: 137-149.

Whitehead, D. and Jarvis, P.G. (1981). Coniferous forests and plantations. Water Deficits and Plant Growth. Volume 6 Ed. T.T. Kozlowski. Academic Press, NY. Pp. 49-152.

Whitehead, D., Edwards, W.R.N. and Jarvis, P.G. (1984). Conducting sapwood area, foliage area, and permeability in mature trees of *Picea sitchensis* and *Pinus contorta*. Canadian Journal of Forest Research **14**: 940-947.

6. ACKNOWLEDGMENTS

Many people and several organisations have input ideas, practical assistance, financial help or all of these into this project; which was the outcome of several diverse ideas. Assistance, both practical and financial, from the industry partners; Auspine Ltd, CSR Timber Products Ltd and Forestry South Australia, and funding from the FWPRDC have been essential to the viability of this project.

We would also like to thank Dr Sadanandan Nambiar for his enthusiasm, Drs Clive Carlyle and Barrie May for their help with ideas and for providing some measurements vital to this project.