Quantifying Groundwater Recharge Under Plantations in South East South Australia

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Cover Photograph:

Juvenile Blue Gums in the Wattle Range, Penola
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EXECUTIVE SUMMARY

The prosperity of South East SA is reliant primarily on the region's extensive, natural, unconfined aquifer system. Sustainable management of the region's groundwater resources requires a sound understanding of the quantity of groundwater recharge under various land uses. To accurately assess groundwater recharge, it is essential recharge under plantation land, which occupies about 14% of the Lower South East of SA, be accurately quantified. Previous research has indicated that during the period of full canopy closure, groundwater recharge under forestry plantations is negligible and plantations extract groundwater at locations with <6 m median depth to groundwater. However, plantation forestry involves periodic harvesting and replanting of the trees. For a period of 6 to 18 months after harvesting, the land is in a fallow state, with little or no vegetation cover. For the first year or two after replanting, the trees are very small, and weeds are partly or completely controlled, potentially resulting in substantially lower evapotranspiration, and allowing groundwater recharge. Prior to this study, the quantity of groundwater recharge for the period between harvesting one rotation and canopy closure of the next had not been measured in these plantations.

This project quantified monthly rainfall, evapotranspiration and changes in root-zone soil water at forestry plantation sites in South East South Australia for approximately 1 year prior to forest harvesting and for up to 3 years of the next rotation (during the period of fallow and when the replanted trees were less than 2 years old). Measurements were undertaken using sapflow sensors, mini-evaporation lysimeters, neutron moisture meter and through-fall troughs. From these measurements, the quantity of groundwater recharge was estimated. During the final year of the project, these estimates were validated against independent direct measurements of deep drainage at each site. An empirical model of evapotranspiration and groundwater recharge up to plantation age 2 years was developed.

At two sites, evapotranspiration was monitored for the final year of the previous rotation. Annual evapotranspiration at these sites was consistent with measurements collected at other sites in the region over the previous 9 years. At one site with >6 m depth to groundwater, the plantation used all of the rainfall. At another site with groundwater present at ~3.5 m depth, the plantation used all of the rainfall, plus additional groundwater. At a third site, monitoring only began after the previous rotation had been harvested.

At all three sites, the soil fully wet up in the first autumn and winter after harvesting. From then on, for the period prior to replanting, and for the first 2 years after replanting, any rainwater that drained to below ~1 m depth probably contributed to groundwater recharge.

Evapotranspiration from fallow land and plantations <1 or 2 years old was approximately 300 to 440 mm per year, and varied little with rainfall. Qualitatively, weed cover appeared to have the greatest influence on evapotranspiration during this period of the rotation. Once the soil had re-wet after harvesting, groundwater recharge was estimated to be equal to the difference between rainfall and evapotranspiration.

A simple empirical model of the relationship between groundwater recharge and rainfall was derived from the data. At sites with good weed control after replanting, this model can be applied to *Pinus radiata* D. Don plantations aged up to 2 years and for *Eucalyptus globlus* Labill. plantations up to 1 year old. Model predictions agreed well with estimates of recharge based on watertable fluctuations observed at two plantation sites by Mitchell and Correll (1987). Recharge initially has to be discounted in the fallow period, to account for the deficit in soil water at the end of the previous rotation. The model can be applied to a range of average annual rainfall rates in the region to estimate recharge interception by plantations, taking into account rotation length, rainfall and location.

However, some uncertainties remain. The amount of recharge occurring between plantation age 2 years and canopy closure in *P. radiata* and between age 1 and canopy closure in

E. globulus still has not been accurately measured, nor has recharge occurring after forest thinning operations. Additional research is recommended to address these knowledge gaps.

1. INTRODUCTION

South East South Australia relies heavily on its groundwater resources for town, stock and domestic water supplies, for industrial uses and to supply high value irrigated pasture and crops. The region's water dependent ecosystems are also believed to rely, at least partly, on groundwater for their survival (Cook *et a*l. 2008).

The Lower Limestone Coast Prescribed Wells Area is a prescribed groundwater management area under the South Australian *Natural Resources Management Act 2004*. As such, a Water Allocation Plan (WAP) must be developed by the South East Natural Resources Management Board and updated as circumstances require. The plan aims to ensure long-term sustainable management of the region's groundwater resources.

To ensure long-term sustainability of groundwater use, in the absence of accurate estimates of groundwater recharge and extractions, allocations need to be very conservative. Improved accuracy in estimates of groundwater recharge can potentially allow increased allocations without increasing the risk of over-allocation. About 90% of the groundwater used in the South East is derived from an extensive, unconfined, shallow groundwater aquifer system, known as the Tertiary Limestone Aquifer (South East Natural Resources Management Board 2008). Recharge of this aquifer is mostly via diffuse local recharge, which in the long-term is determined by the difference between annual rainfall and annual evapotranspiration. Any change in land use which alters the quantity of evapotranspiration will also alter the amount of groundwater recharge. Accurate estimates of total groundwater recharge across the region need to account for differences in recharge rates occurring under different land uses and vegetation types.

Plantations of *Pinus radiata* D.Don have been grown and processed in South East SA for many decades. The area of *P. radiata* in the lower South East currently stands at around 100,000 ha and is increasing at about 1 to 2 % per year.

Since 1999 there has been a rapid increase in the area planted to Tasmanian blue gums (*Eucalyptus globulus* Labill), from only a few hundred ha in 1998 to approximately 45,000 ha in 2008. Between 1998 and 2008, the combined area of *P. radiata* and *E. globulus* forestry plantations increased by almost 50% and by 2008 the total plantation area for the region was 146,000 ha, or ~14% of the Lower South East.

It is known that in general, deep rooted vegetation, such as trees, have higher evapotranspiration for a given rainfall, than shallow-rooted dryland grass and crops. Research in the 1960s and early 1970s indicated groundwater recharge under *P. radiata* plantations in South East South Australia was either zero (Holmes and Colville 1970, Allison and Hughes 1972) or substantially lower than under grassland (Colville and Holmes 1972). Direct measurements of water use by plantations over the past decade confirm recharge is usually zero in the period of the rotation after canopy closure. In addition, closed-canopy plantations extract groundwater at locations where the median depth-to-groundwater is <6 m and there are no root impeding layers (Benyon and Doody 2004, Benyon *et al*. 2006, Benyon *et a*l. 2008).

Given the extent of the plantation area in the LLCPWA, it is important to accurately estimate recharge rates under plantation land. In the first WAP for the LLCPWA in 2000, it was assumed recharge under native and plantation forests in the region was zero. However this assessment was considered more precautionary than factual. Since then it has been recognised that, because forestry plantations are periodically harvested and regrown, there is a period in each rotation when the land is either in a fallow state, or has a very sparse cover of weeds and small trees. During this period, evapotranspiration is expected to be low, and therefore it is possible groundwater recharge will occur.

In addition to the 14% forestry plantations, the dryland agricultural landscape of the region comprises a mix of annual and perennial pastures, dry grown crops, fallows (chemical and cultivated), hard grazed pasture and dormant pastures. Recharge may occur at different rates under these different land uses and is also strongly influenced by climate and soil. To account for the combined effects of these various factors on actual recharge rates, Brown *et* *al*. (2006) estimated annual recharge rates for the various groundwater management areas across the LLCPWA using a water table fluctuation method. Groundwater recharge usually occurs each winter and spring, resulting in a rise in the watertable at this time of year. These rises can be used to estimate the quantity of recharge. For example, assuming aquifer specific yield of 10%, a rise in elevation of the watertable by 1 m indicates 100 mm of groundwater recharge (Brown *et al*. 2006). Depending on aquifer characteristics, these rises can reflect the amount of recharge occurring up to several kilometres from the observation well.

Mitchell and Correll (1987) observed fluctuations in watertable height in the first 7 years of first and second rotation *P. radiata* plantations near Tantanoola. During winter and spring of the first 2 years after planting, when rainfall averaged 903 mm year^{-1}, the watertable rose by an average of about 5 m in each winter-spring period. Based on the Brown *et al*. (2006) water table fluctuation method, this would indicate ~500 mm recharge in each of these 2 years after planting. After extensive areas of *P. radiata* were burnt in February 1983 and subsequently salvaged logged, watertable heights in the burnt and harvested areas rose by 1 to 4.5 m (Dillon *et al*. 2001), indicating the possibility of several hundred mm of recharge.

Based on some assumptions about the amount of recharge occurring at the beginning of each rotation, and in the case of *P. radiata*, after each thinning (Table 1), it is generally agreed that forestry plantations intercept less than 100% of groundwater recharge (DWLBC in prep.).

For the purposes of estimating recharge interception, typical rotations for *P. radiata* and *E. globulus* were defined in consultation with forest industry stakeholders. The typical *P. radiata* rotation is 36 years (35 years trees plus 1 year fallow) and includes four thinnings. When the recharge rates in Table 1 for this species are summed across this typical rotation, recharge is estimated to be reduced by 83% compared to average recharge from agricultural land. Similarly, assuming an 11 year rotation (10 years of trees plus 1 year fallow) with no thinning, recharge interception is estimated to be 78% for *E. globulus*.

To estimate the absolute recharge interception by plantations in a given groundwater management area, these percentage rates are multiplied by the mean recharge rate for that area, and divided by 100. For example, the estimated recharge rate for the Hundred of Young is 200 mm year^{-1} (Brown *et al*. 2006). Based on Table 1 and the typical plantation rotations, annualised average recharge would be 34 mm year^{-1} under *P. radiata* plantation and 44 mm year^{-1} under *E. globulus*. As indicated in Table 1, the most recharge is assumed to occur in the first 3 years of each rotation. In the Hundred of Young, for example, total recharge of 600 mm would be assumed for *P. radiata*, compared with 240 mm in the next 3 years and 400 mm total in the final 29 years of the rotation. In *E. globlus*, in Young, total recharge is assumed to be 480 mm in the first 3 years and then zero in the next 8 years of each rotation. Observations from 22 closed-canopy plantation sites across the Green Triangle, including nine *P. radiata* and 13 *E. globulus* sites, confirm there is little or no recharge during the period of canopy closure (Benyon *et al*. 2008).

As at least half of the recharge is assumed to occur in the first 3 years of each rotation, it is important to verify the accuracy of these estimates. If recharge in the early years of the rotation is substantially less than the deemed rates, there is a risk of over-allocation of the region’s water resources. If, however, recharge rates are greater than the deemed rates, groundwater may be un-necessarily tied up in allocation to plantations.

To address this, a study of recharge rates in the first 3 years after harvesting was undertaken between spring 2005 and autumn 2009. This report describes the measurement methods and results of this study. Observed rates of groundwater recharge in the 2 – 3 year period following harvesting were compared with the assumed rates from Table 1. We tested a null hypothesis that up to year 2 after replanting, recharge rates are the same as those shown in Table 1.

Table 1. Assumed recharge rates for plantations as a percentage of groundwater management area recharge.

Year of rotation	*P. radiata*	*E. globulus*
0	120	120
1	100	80
2	80	40
3	60	0
4	40	0
5	20	0
After year 5	0	0
Year after thinning	50	Not applicable

2. METHODS

2.1. Field site descriptions

Three field sites were selected in July 2005 (Table 2) and visited approximately monthly to early April 2009. Site selection was undertaken in consultation with representatives of the forest industry and was largely determined by harvesting schedules. Sites that were to be harvested in 2005 or 2006 were required. No *E. globulus* plantations were scheduled for harvest in the region until 2008, however, ForestrySA made a small demonstration planting (<3 ha) available for the project which was able to be harvested earlier. The two *P. radiata* plots were located in compartments harvested as part of normal forestry operations and were treated in the same way as the surrounding plantations.

At each site, a single measurement plot was established, 20 m x 20 m in area. Measurements included rainfall, evaporation from the soil surface and root zone soil water. Transpiration and throughfall were monitored prior to harvesting the plantations at Sites 2 and 3. For the final year of the study, deep drainage at all three sites was measured directly using drainage meters.

Table 2. Details of the three field sites.

	Site 1	**Site 2**	**Site 3**
Species	*P. radiata*	*P. radiata*	*E. globulus*
Location	Zone 2A, ~10 km east of Tarpeena	Glenburnie, ~10 km SE of Mt Gambier	Young, ~10 km NW of Mt Gambier
Latitude **Longitude**	37° 36’ 30” S 140° 56’ 24” E	37° 43’ 17” S 140° 42’ 06” E	37° 54’ 50” S 140° 51’ 25” E
GMA recharge rate (mm year^{-1})	140	150	200
Long-term mean rainfall (mm year^{-1})	681	782	736
Depth to watertable (m)	4.5	>6	3.5
Soil	Sand to 1 m, sandy clay to 3 m, then sand	Sand with limestone to 2.5 m, then limestone	Sand to 1 m then sandy clay
Soil water monitoring period	1/11/2005 to 3/04/2009	1/11/2005 to 3/04/2009	16/11/2005 to 3/04/2009
Harvested	April 2005	September 2006	June 2007
Replanted	August 2006 (failed) May 2007	June 2007	Not replanted

Site 1 was flat with a duplex soil of sand to 1 m depth, light sandy clay to 3 m and sand below 3 m. Groundwater was present at approximately 4.5 m depth. Mean precipitation from 1961 to 1990, obtained using the Silo Data Drill, was 681 mm year^{-1}. When field instrumentation began in July 2005, the site was in a fallow state, following harvest of the previous *P. radiata* crop in autumn 2005. It had recently been chopper rolled, leaving a cover of mulched logging debris consisting of dead pine needles, branches, pine cones and bark. The site remained fallow until it was replanted with *P. radiata* seedlings in August 2006. Due to abnormally low rainfall, there was very little weed growth. Routine aerial spraying with herbicide in spring 2006 further minimised weed growth. Continued low rainfall from September 2006 to April 2007 resulted in poor survival (<50%) of the young *P. radiata* seedlings. Consequently the site was replanted a second time in late May 2007. More than 90% of the replanted trees survived. There was very little weed growth after that time, due to continuing below average rainfall and routine aerial spraying with herbicide. When measurements of evapotranspiration and soil water ceased in early April 2009, 23 months after the second replanting, the seedlings ranged in height from approximately 0.5 to 1.8 m

(Figure 1). Planting density was not measured but was the standard density used by the plantation owner.

Site 2 was located in a mid-slope position, on gently undulating land, with a slope of <5°. It has 2 to 3 m of loamy sand over a fine-grained, soft limestone. Limestone fragments are present from about 0.5 m depth. Long-term mean rainfall was about 782 mm year^{-1} (Silo Data Drill). The site was initially instrumented (see below) in August and September 2005, when still a mature *P. radiata* plantation. Equipment was removed in August 2006 prior to harvesting of the trees in September. Thus, no data was collected until equipment was reinstalled in November 2006. After harvesting, the site was covered with logging debris and bare loamy sand soil. Three of the five access holes for monitoring soil water could not be relocated. Three replacements were installed in June 2007. The site was chopper rolled in February 2007 causing damage to some of the evaporation monitoring equipment. Some equipment was damaged again in May 2007 during deep ripping in preparation for replanting. All damaged equipment was replaced within 1 month. *P. radiata* seedlings were planted in mid June 2007 and weeds were controlled by strip spraying in spring 2007. When measurements ceased in early April 2009, almost 22 months after replanting, the site had a light cover of weeds, mostly in the inter-rows, and the *P. radiata* seedlings were approximately 0.5 to 1.2 m tall (Figure 2 and Figure 3). As with Site 1, planting density was not determined but was the standard used by the plantation owner for that area.

Figure 1. Two views of Site 1, 21 months after replanting.

Figure 2. View of Site 2, 20 months after replanting.

Figure 3. Close up view of Site 2 illustrating the weed cover was light and patches of bare soil were still visible between individual weeds and small pines 20 months after replanting

Site 3 was located in a mid slope position on gently undulating land, with a slope of <5°. It has a sandy soil to about 1 m, over a light sandy clay and had a mean rainfall of 736 mm year^{-1} (Silo Data Drill). The *E. globulus* plantation was 12 years old when monitoring equipment was installed in November 2005. Equipment was removed in May 2007 to enable harvesting in winter 2007. After harvesting the site had a heavy cover of eucalyptus branches, bark and dead leaves, with patches of bare, sandy soil. Monitoring equipment was re-installed in October and November 2007. Coppice growth from the cut stumps was sprayed with herbicide by the land owner in autumn 2008 when the shoots were up to 2 m tall. This was largely effective but some of the shoots did survive (Figure 4). This is common practice for *E. globulus* plantation when the intention is to re-establish the plantation from seedlings. No other weed control was undertaken. Consequently grass growth was moderately heavy in patches at this site (Figure 4) and probably atypical of *E. globulus* plantations in the region as the land owner intended to convert the site to *P. radiata* plantation.

Figure 4. View of Site 3, about 20 months after harvesting.

2.2. Measurement methods

2.2.1. *Rainfall, throughfall and interception loss*

Rainfall totals at each site were recorded in 100 mm diameter, bulk rain gauges located in the nearest open area. At Site 1, because the plantation had already been harvested before measurements commenced, and there were no large trees within several hundred metres of the study plot, the rain gauge was located next to the access road, only about 30 m from the centre of the plot. An additional five gauges were located within the plot. The young trees did not begin to overtop these until autumn 2009. Thus, for most of the study period, there was either no vegetation cover at all, or a cover of only very small trees (Figure 5). The five rain gauges within the plot were therefore able to be used to obtain a more accurate measure of rainfall for most of the study period.

At Sites 2 and 3, the rain gauges were located in large clearings less than 0.5 km from the research sites. As with Plot 1, after harvesting of the plantation, five additional rain gauges within each plot were used to obtain a more accurate rainfall estimate until overtopped by weeds or young trees.

At Sites 2 and 3, for the 12 to 18 months prior to harvesting, throughfall under the tree canopy was measured in eight collectors in each plot. Each collector consisted of a V-shaped aluminium trough, 1.2 m long by 0.14 m wide, draining through a funnel into a closed, 20 L container (Figure 6). The quantity of throughfall collected was measured at each monthly site visit. Stem flow was not measured, but based on previous observations of stem flow in plantations in the region (CSIRO, unpublished data), was assumed to be 5% of rainfall for the *P. radiata* plantation at Site 2, and 2% of rainfall at the *E. globulus* site. Net rainfall under the canopy was estimated as the measured throughfall plus the allowance for stem flow of 5% or 2% of rainfall. Interception loss was calculated as rainfall in the open less net rainfall under the canopy.

The throughfall collectors were removed shortly before harvesting of the plantations and were not re-installed. In the final few months of the study, when weeds and the young seedlings began to over top some of the five rain gauges in each plot, interception loss was estimated as the difference between rainfall measured in the open and that measured in the five rain gauges in the plot.

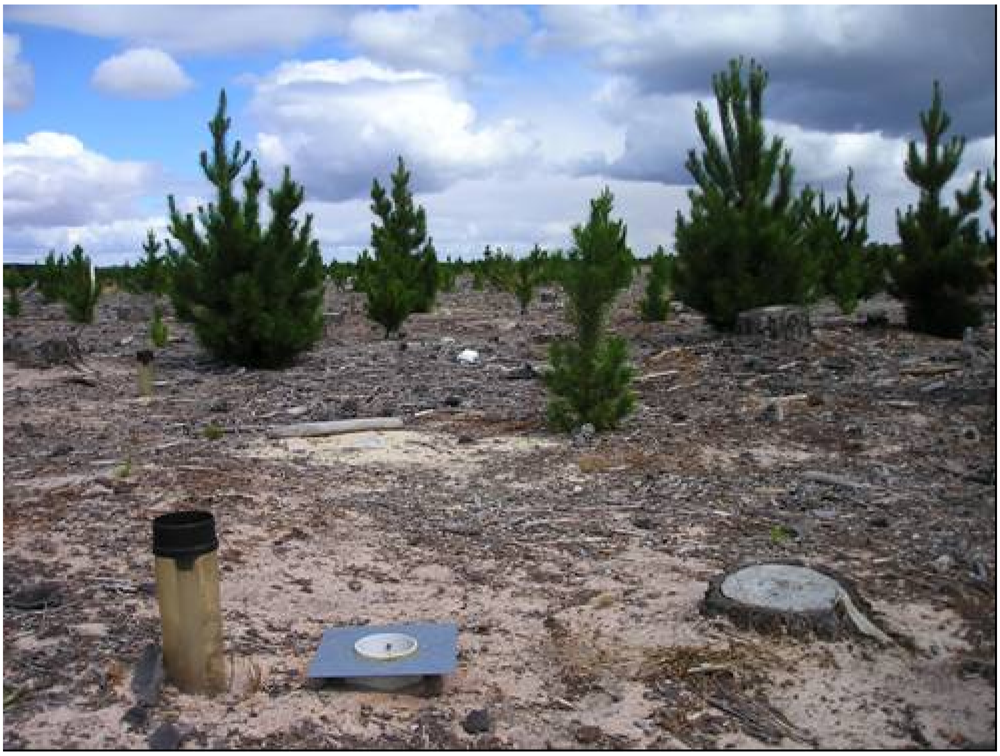

Figure 5. View of Site 1, 21 months after replanting, showing a rain gauge and lysimeter.

Figure 6. Close up view of a throughfall collector.

2.2.2. *Transpiration prior to harvesting*

Prior to harvesting the plantations at sites 2 and 3, daily transpiration from the forest canopy was estimated based on sapflow measurements collected every 30 minutes in six sample trees per plot (Figure 7). However, this report is principally focused on quantifying the quantity of groundwater recharge occurring in the 2 – 3 year period after harvesting. Consequently, we present only a brief summary of pre-harvesting water balances, and have not described the sap flow measurements in detail here. The methods used were identical to those described for 19 other closed-canopy plantation sites in the region (Benyon and Doody 2004, Benyon *et al*. 2006, Benyon *et al*. 2008).

Figure 7. Equipment used to measure sap flows and determine transpiration at Sites 2 and 3 prior to harvesting.

2.2.3. *Evaporation from the soil surface*

Evaporation from the surface soil for the period between each field visit (nominally 1 month) was determined using five mini-lysimeters (Figure 8) per plot. Weeds were allowed to grow in the lysimeters, so evaporation includes weed transpiration. However, the lysimeters were not large enough to include tree seedlings. Consequently our estimates of evapotranspiration during the post replanting period do not include transpiration by the young tree seedlings. Each lysimeter consisted of a rain gauge and a 0.6 m (Sites 1 and 3) or 0.3 m (Site 2) deep, 0.1 m diameter column of soil, inside a PVC sleeve, suspended in a pit over a container so that the soil surface of the column was at ground level. The end cap at the bottom end of the PVC sleeve was perforated to allow drainage water to escape. A funnel and storage container collected any water that drained through the soil column. The soil in the lysimeters was collected by driving the PVC into the surface soil using a rubber mallet to obtain an in-tact core. This ensured the soil in the lysimeters was of a similar density and moisture content to that of the surrounding soil. At each visit the total amount of rainfall and drainage collected was measured, and the soil column was weighed.

Figure 8. Equipment used to measure evaporation from the soil surface. From left to right a rain gauge, soil column inside PVC sleeve, drainage collector and outer PVC housing buried in the ground.

Equation 1 was used to estimate the total evaporation from the surface soil for the period. All values in Equation 1 are in mm.

$$E = P - \mathrm{D} - (W_c - W_p) \qquad [1]$$

where: E represents evaporative loss from soil surface, leaf litter and weeds.

P represents total precipitation for the period, measured in a rain gauge placed near the soil column but not so close as to intercept rain falling into the soil column.

D represents the volume of drainage collected beneath the soil column and converted to a depth in mm.

W_c- W_p represents the change in weight of the lysimeter during the period, expressed as an equivalent depth of water in mm, assuming water has a density of 1000 kg m^{-3}.

2.2.4. *Root zone soil water*

During each monthly site visit, the volumetric water content of the soil was measured using a neutron probe (CPN Hydroprobe, Figure 9) at 0.3 m depth intervals in each of five stainless steel access tubes to a maximum depth of 4.8 m at site 1, 5.8 m at Site 2 and 5.4 m at Site 3. Neutron counts were calibrated to volumetric water content of the soil based on soil samples collected from the access tube holes at the time of installation.

Groundwater was present at 4.5 m depth at Site 1 and 3.5 m depth at Site 3, and therefore at these two sites, the depth of soil water measurements covered the possible maximum root depth, assuming the fine tree roots would not grow into the saturated zone. At Site 2, depth to the groundwater was not measured. However, based on data from groundwater observation wells located in that GMA several km from the site, and the location of the research site in an elevated position in the landscape, depth to groundwater was assumed to be much greater than 6 m. This may have allowed the tree roots to reach deeper than 6 m. During the year of monitoring prior to harvesting the plantation at this site, comparison of net rainfall and evapotranspiration with changes in soil water indicated that over summer, and early autumn, the trees were obtaining a small amount of water from deeper than 6 m and therefore that root depth may have been greater than 6 m.

Figure 9. Using a neutron moisture meter to measure soil water.

2.2.5. *Deep drainage*

Drainage meters (Draingauge, Decagon, Pullman Washington, USA, Figure 10) were installed at each site after completion of all machine operations associated with harvesting and preparation of each site for replanting. The Draingauge is a passive wick capillary lysimeter that was designed specifically to allow direct measurement of deep drainage (Decagon Devices Inc., 2004). The meter is buried below the root zone of the vegetation (Figure 10). A 0.66 m deep x 0.20 m diameter convergence control tube directs a representative sample of drainage water to a fibreglass wick. Gee *et al*. (2002) determined that a convergence tube of 0.6 m length was sufficient to ensure accurate drainage measurements in most soils. The wick maintains a tension on the water at the bottom of the soil profile and directs drainage water into a measurement reservoir. A water depth sensor detects the depth of water in the reservoir. This depth is recorded on a data logger at intervals set by the user. We recorded water level depth every 30 minutes. The water reservoir holds the equivalent of 1 mm of drainage water. Once full, the reservoir automatically syphons to a larger sampling reservoir, from which water samples can be withdrawn for chemical analysis. Excess reservoir water drains into the soil below the gauge through an overflow port. We were interested only in the quantity of the deep drainage, not its chemical composition, so we did not extract water samples for analysis. We determined the quantity of deep drainage in mm, by counting the number of times the smaller measurement reservoir filled and emptied, assuming each syphoning event indicated 1 mm of deep drainage had been collected.

At all sites, the drainage meters were installed by excavating a suitable sized access hole and back filling into the convergence tube above the wick with soil taken from the hole. The soil layers were placed in the same order as removed, and packed to a similar density. Disturbance of the soil above the Draingauge was unavoidable. This may have influenced the propensity of the soil to drain. The surface soil being of sandy texture lacked any well-defined structure. Any preferential flow paths present before installation of the Draingauges, such as old root channels from the previous rotation, would have been destroyed during installation. As noted below, a period of between 6 and 12 months elapsed between installing the Draingauges and obtaining the correct data loggers, and therefore considerable settling of the soil would have occurred before data collection began.

Three Draingauges were installed at Site 1 and two at Site 2 in autumn 2007, with the fibreglass wick at 2.2 m depth. Two Draingauges were installed at Site 3 in spring 2007 with the wick at 1.5 m depth. The wrong data loggers were used initially and no drainage data were obtained until the correct loggers were connected to the meters in early 2008. Thus, only 1 full year of drainage data were obtained from early April 2008 to early April 2009.

Figure 10. A Draingauge installed under herbaceous vegetation. Photograph from Decagon Devices Inc.

2.2.6. Data analysis

For the period prior to harvesting at Sites 2 and 3, monthly evapotranspiration (ET) was calculated as the sum of interception, soil evaporation and transpiration. As with most forestry plantations in the region, Site 2 had no understorey. Site 3 had light understorey of grass (species not determined).

For each month the total ET and rainfall was compared with the measured change in the volumetric water content of the root zone to infer whether net groundwater recharge (or runoff) or groundwater uptake had occurred. Annual total rainfall, ET and net water balances were calculated. Statistical confidence intervals for mean annual ET at each site were estimated based on the variation in sap velocities between individual sample trees after Benyon *et al*. (2006).

For the period after harvesting, the main source of evaporative loss was from the bare soil surface and light weed cover. Because trees were either absent or very small during this time, we assumed evaporation from the lysimeters provided an accurate measure of ET. Again, for each measurement period, total ET and rainfall was compared with the measured change in water content of the soil to estimate groundwater recharge using Equation 2:

$$Q_{wt} = P - ET - (S_c - S_p) \qquad [2]$$

Where: Q_{wt} is estimated quantity of deep drainage to the water table

P = precipitation

ET = evapotranspiration

S_c and S_p are the current and previous volumetric water content of the soil to the maximum depth of measurement

For the final year of measurement we verified these groundwater recharge estimates by comparing them with deep drainage measured directly in the Draingauges. Statistical confidence intervals for annual ET were estimated based on the variation between evaporation lysimeters.

3. RESULTS

3.1. Site water balances prior to harvesting

At Site 2, rainfall and ET were monitored for a full year prior to harvesting. Total ET (690 mm) was higher than total rainfall (649 mm) by 41 mm (Figure 11). However, the 95% statistical confidence interval for total ET was ±48 mm, and therefore total ET was not statistically significantly different from total rainfall.

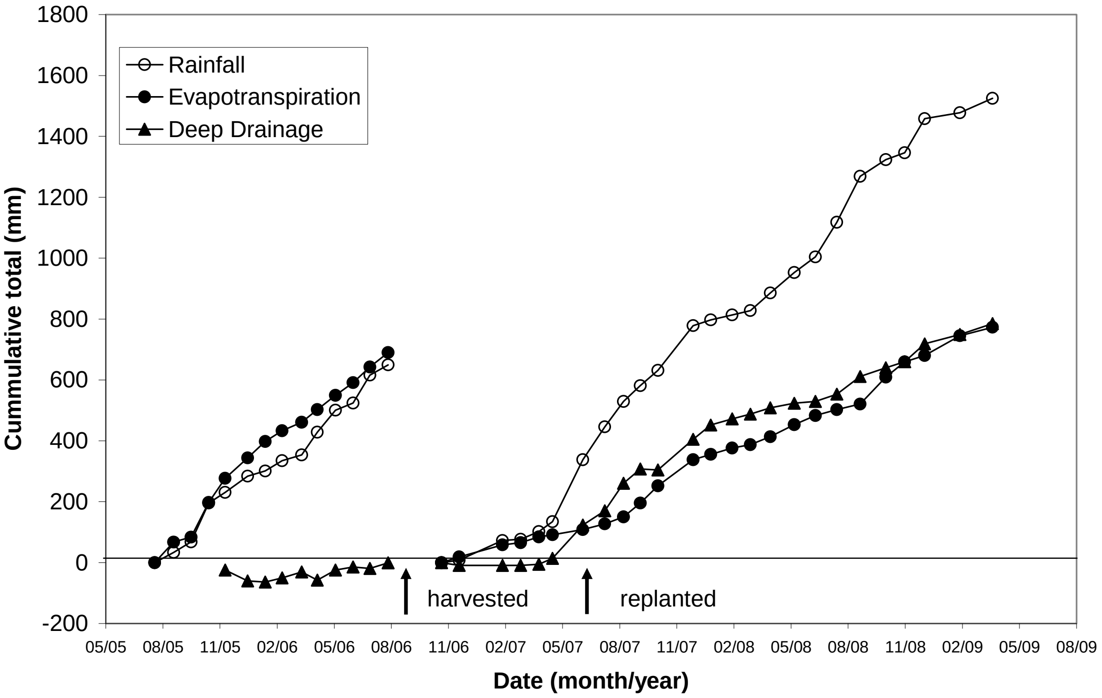

Figure 11. Cumulative rainfall, ET and estimated recharge before and after harvesting at Site 2.

Prior to harvesting, soil water was measured for 9.4 months, from 1 November 2005 to 14 August 2006. During this period, total ET of 493 mm compared with total rainfall of 454 mm (Figure 11). However, total soil water decreased by 38 mm, meaning the trees had drawn 38 mm of water from the top 5.8 m of soil in addition to rainfall input. Thus, only 1 mm of the total ET during this period could not be accounted for by rainfall and depletion in soil water. In the 3 months prior to commencement of soil water monitoring, ET of 197 mm compared with rainfall of 195 mm. We conclude that prior to harvesting at this site, the plantation was using all of the available rainfall, and that it was not accessing additional groundwater. This is consistent with previous observations in the region for closed canopy plantations with >6 m depth to groundwater (Benyon and Doody 2004, Benyon *et al*. 2006, Benyon *et al*. 2008).

At site 3, ET, rainfall and changes in soil water were monitored for 1.5 years prior to harvesting. ET totalled 1495 mm for this period compared with rainfall of only 778 mm. Soil water decreased by 59 mm, meaning 658 mm of ET could not be accounted for by rainfall and depletion in soil water (Figure 12). The 95% statistical confidence interval for total ET was ±239 mm, meaning ET was significantly more than could be accounted for by rainfall and depletion in soil water. The trees must therefore have obtained additional water from groundwater present at 3.5 m depth. This is consistent with previous observations in other closed canopy plantations in the region established at locations with < 6 m depth to groundwater (Benyon and Doody 2004, Benyon *et al*. 2006, Benyon *et al*. 2008).

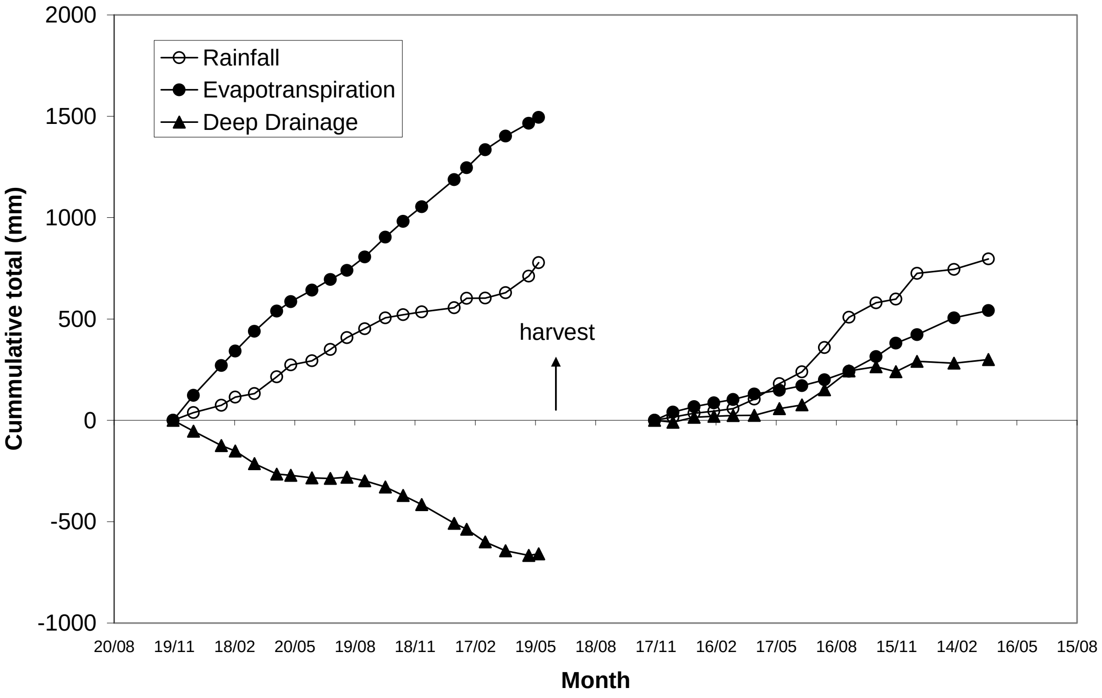

Figure 12. Cumulative rainfall, ET and estimated recharge before and after harvesting at Site 3.

3.2. Site water balances and recharge after harvesting

Site One

Figure 13 displays the cumulative total ET, rainfall, and estimated groundwater recharge for the entire monitoring period at Site 1. In the 3.61 years of monitoring, rainfall totalled 1701 ± 38 mm (95% statistical confidence limits), or an average of 471 mm year^{-1}, which is about 31% below the long-term mean for this site. ET totalled 1098 ± 92 mm (304 mm year^{-1}), and over the 3.42 years of soil water monitoring there was a net decrease in soil water of 42 ± 29 mm. The water balance estimates (Equation 2) indicate 690 ± 92 mm (191 mm year^{-1}) total groundwater recharge during this period.

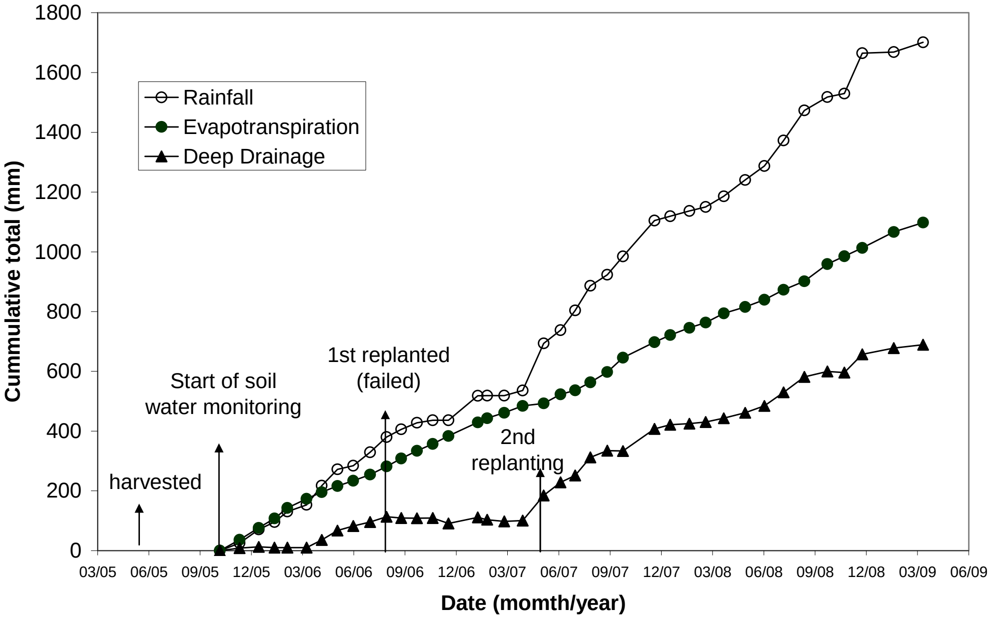

Figure 13. Cumulative rainfall, ET and recharge after harvesting at Site 1.

The first 20 months of monitoring was very dry, with only 536 mm of rain for that period (321 mm year^{-1}), which is only 47% of the long-term mean. In the first 9 months after the first replanting, the site received only 165 mm of rain (Figure 13). About 100 mm of recharge occurred during the fallow period in late autumn and winter 2006. There was then no recharge until heavier rains began in late April 2007 (Figure 13). From then on, recharge occurred in most months. In the wettest year (April 2007 to April 2008), rainfall totalled 677 mm year^{-1}, evapotranspiration 316 mm year^{-1} and recharge 350 mm year^{-1}.

Annual water balances for the final full three years of measurements (April to March 2006/07, 2007/08 and 2008/09) are detailed in Table 3. Despite annual rainfall totals varying considerably from year to year, annual ET changed only slightly, from a low of 296 mm in 2006/07 (rainfall 377 mm) to a high of 316 mm in 2007/08 (rainfall 677 mm). There was little change in soil water from year to year and therefore estimated recharge was approximately equal to the difference between rainfall and ET. Because the latter was almost constant from year to year, but rainfall varied substantially, recharge also varied substantially from year to year.

Table 3. Site annual water balances for the period after harvesting at each site.

	Site 1			Site 2		Site 3
	2006-07	2007-08	2008-09	2007-08	2008-09	2008-09
Rain (mm)	374	677	549	789	659	740
ET (mm)	296	316	313	340	371	439
SW change (mm)	-8	10	-19	21	4	25
Recharge (mm)	86	350	254	428	285	276
Draingauge (mm)			191		298	384
GMA recharge rate (mm/year)		140		150		200

Figure 14 shows the water content of the soil at its wettest and driest in the post-harvesting period at Site 1 between 1/11/2005 and 3/04/2009. There was little variation in water content over time below a depth of about 1 m, indicating drying and re-wetting of the profile was only occurring in the top 1 m. The profile below this depth had fully re-wet in the winter and spring prior to commencement of monitoring soil water, and there was no drying due to ET below about 1 m depth. Any deep drainage reaching > 1 m depth would have continued to drain through to the water table present at about 4.8 m.

Figure 15 displays cumulative drainage during the final year of monitoring at the same site, estimated by three different methods: drainage collected at the bottom of the lysimeters at 0.6 m depth, in the Draingauges at 2.2 m depth and estimated at 4.8 m from the soil water balance measurements. Note that drainage through the lysimeters was used in estimating ET for the water balance, so the estimate of deep drainage to 4.8 m from the water balance is not independent of the direct measure of drainage to 0.6 m. However, the drainage measured in the Draingauges is an independent measure. All three methods showed a similar pattern of drainage through the year, and the accumulated totals by the end of the period were similar. The Draingauge data provides verification that the soil water balance technique gave a realistic estimate of deep drainage.

Site Two

Figure 11 displays the cumulative total ET, rainfall, and estimated groundwater recharge at Site 2. In the 2.4 years of post-harvesting monitoring, rainfall totalled 1525 ± 14 mm, or an average of 634 mm year^{-1}, which is about 19% below the long-term mean for this site. ET totalled 773 ± 104 mm (322 mm year^{-1}) and there was a net increase in soil water of 18 ± 17 mm. The water balance estimates (Equation 2) indicate total groundwater recharge of 734 ± 104 mm (301 mm year^{-1}). The estimate of the net change in soil water may not be accurate.

Only two of the original five access tubes were found after harvesting: the remainder were lost under logging slash. Three new access tubes were installed in June 2007.

In the first six months after resumption of monitoring after harvesting, only 134 mm rainfall was recorded. No recharge occurred in this period (Figure 11). Winter 2007 was relatively wet at this site, resulting in 307 mm recharge (Figure 11). After October 2007, recharge occurred in every month. Annual water balances for the final full two years of measurements (April to March 2007/08 and 2008/09) are detailed in Table 3. In the wettest year (2007/08), rainfall totalled 789 mm year^{-1}, evapotranspiration 340 mm year^{-1} and recharge 428 mm year^{-1}, based on the net change in soil water in the two neutron moisture meter access holes monitored for the whole period. There was an increased cover of weeds in the final year, which probably explains higher evapotranspiration (371 mm) despite lower rainfall (659 mm). There was little change in soil water in the final year (a net increase of 4 mm based on all 5 access holes), and therefore net recharge (285 mm) was almost equal to rainfall minus evapotranspiration.

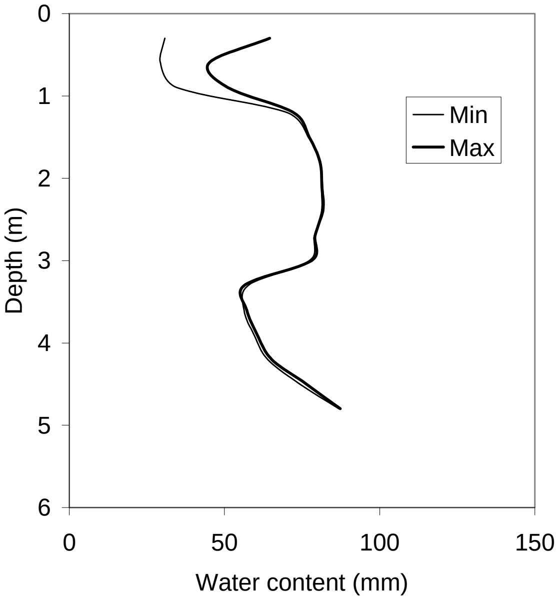

Figure 14. Maximum and minimum soil water content observed at Site 1 in the 3.4 years of monitoring.

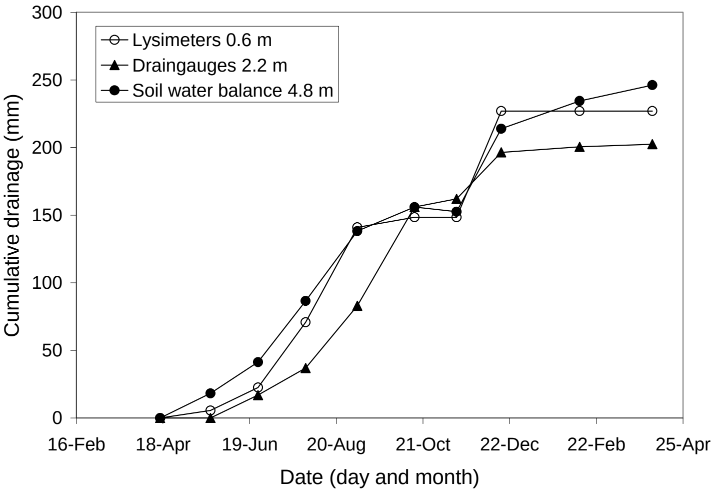

Figure 15. Cumulative deep drainage estimated to 0.6 m (evaporation lysimeters), 2.2 m (Draingauges) and 4.8 m (soil water balance) depth at Site 1 between April 2008 and April 2009.

Figure 16 displays cumulative drainage during the final year of monitoring. Total drainage for the final year was similar for all three methods, indicating most of the rainfall reaching 0.3 m depth continued to drain through the profile. There was, however a longer time lag in drainage water reaching deeper in the profile than at the other two sites. Drainage to 0.3 m ceased by early December, but continued to early February at 2.2 m depth and to early April at 5.85 m. Again the similarity of the pattern of variation through the year and in the total drainage estimated by the Draingauges and the soil water balance method provides confidence in the drainage estimates from the soil water balance method in the previous years.

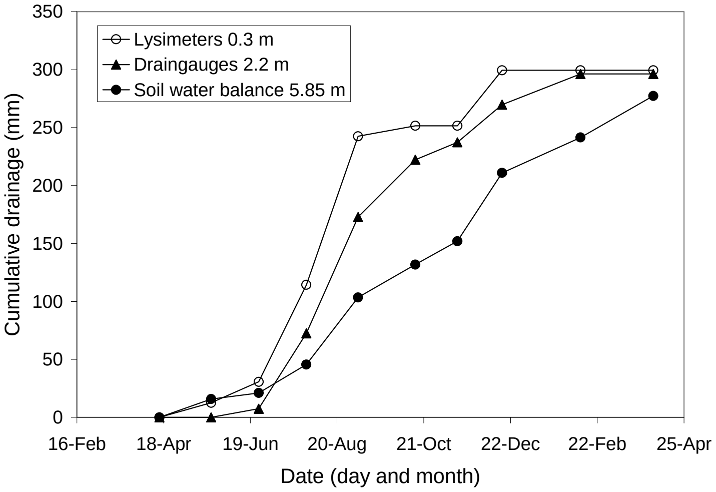

Figure 16. Cumulative deep drainage estimated to 0.3 m (evaporation lysimeters), 2.2 m (Draingauges) and 5.8 m (soil water balance) depth at Site 2 between April 2008 and April 2009.

Site Three

Figure 12 displays the cumulative total evapotranspiration, rainfall, and estimated groundwater recharge at Site 3. In the 1.4 years of post-harvesting monitoring, rainfall totalled 798 ± 18 mm, ET totalled 542 ± 97 mm and there was a net reduction in soil water of 45 ± 40 mm. The water balance estimates (Equation 2) indicate total groundwater recharge of 299 ± 97 mm.

From Figure 17, cumulative drainage during the final year of monitoring followed a very similar pattern for all three methods up to November 2008. After unusually high rainfall between mid November and mid December (127 mm), substantially more drainage was recorded in the Driangauges than collected from the bottom of the evaporation lysimeters or inferred by the water balance method. One of the two Draingauges collected 128 mm during this period compared with only 37 mm in the other. This one large drainage event resulted in higher total drainage in the Driangauges (407 mm) than using the water balance method (308 mm). In early December 2008, a record rainfall total for a single December day of 73 mm was recorded at Mount Gambier Airport < 10 km from Site 3. Unusually intense rainfall might have caused some overland flow and ponding of rainwater above one of the Draingauges, which might have resulted in anomalously high drainage.

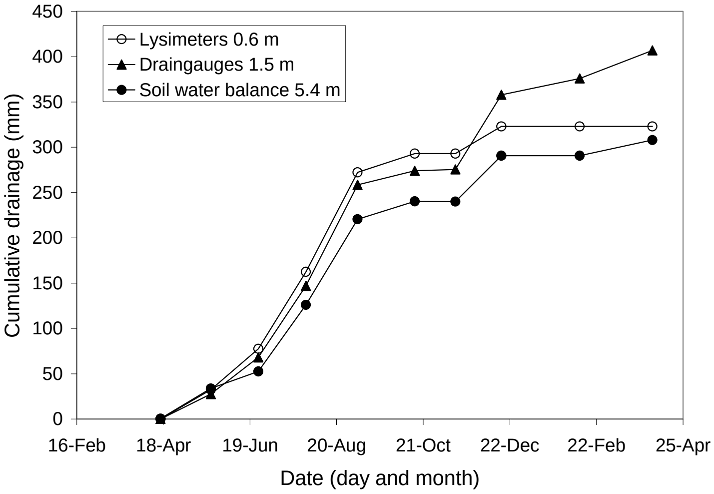

Figure 17. Cumulative deep drainage estimated to 0.6 m (evaporation lysimeters), 2.2 m (Draingauges) and 5.4 m (soil water balance) depth at Site 3 between April 2008 and April 2009.

4. DISCUSSION

4.1. Groundwater recharge under plantation land in the inter-rotation period

Direct measurements of deep drainage in the final year of the study compared well with estimates of deep drainage based on measurements of rainfall, ET and changes in soil water (Figure 15, Figure 16 and Figure 17), providing confidence in the estimates of groundwater recharge based on the soil water balance method in the previous 2 years.

During the fallow period and when replanted *P. radiata* seedlings were <2 years old, ET was relatively low, and did not vary substantially with rainfall (Table 3). Qualitatively, the density of weed cover appeared to have the greatest influence on annual ET during this period of the rotation. Site 1 had no weeds (Figure 1) and the young *P. radiata* seedlings initially died or grew very slowly due to low rainfall. This site had the lowest mean annual ET and it changed little from year to year, despite large inter-annual variation in rainfall. Annual ET post-harvesting was higher at Site 2, which had a more dense cover of weeds (Figure 2) than Site 1, although still obviously light, as bare soil was always evident between the individual weeds (Figure 3). ET increased slightly in the final year of monitoring, despite lower rainfall than in the previous year. The higher ET in the second year may have been related to the presence of a heavier weed cover. Site 3, which had the heaviest cover of weeds (Figure 4), had the highest ET in the final year of monitoring.

Sites 1 and 2 are probably representative of early rotation management of *P. radiata* plantations in the region because they were treated in the same way as the surrounding forestry compartments in which they were located. Site 1 effectively had an extra year of fallow as a result of very low rainfall causing failure of the first replanting. At this site, the period of recharge probably lasted a year longer than usual.

Site 3 does not represent typical early rotation management of *E. globulus* plantations. Because the owner did not intend replanting this site with *E. globulus*, weeds were not controlled in the final year of ET monitoring. ET may therefore have been higher, and groundwater recharge lower, than if the site had been prepared for replanting with *E. globulus* seedlings.

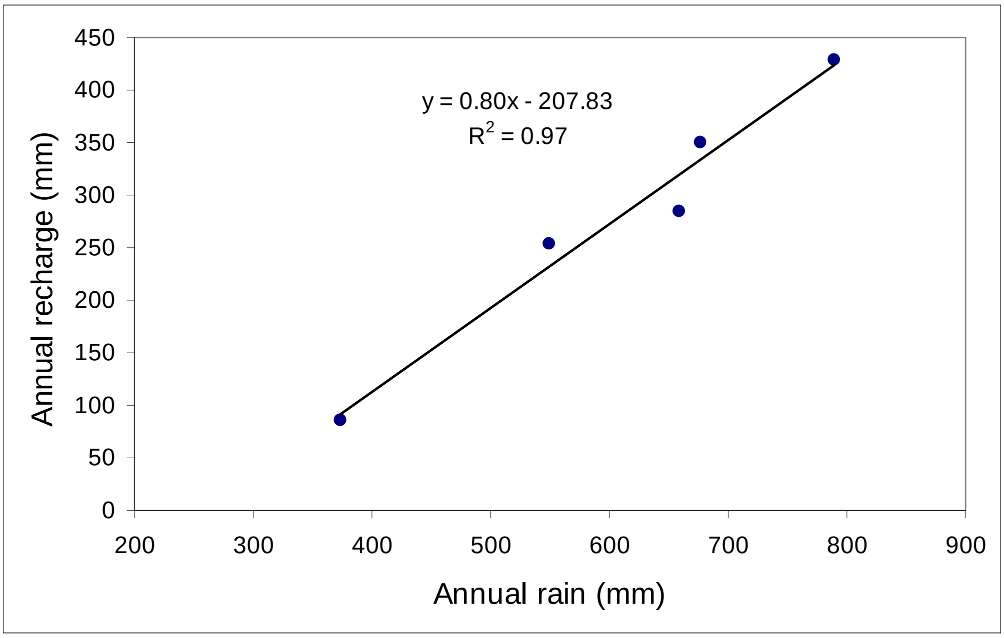

Figure 18. Relationship between annual recharge and annual rainfall for the fallow period and up to 2 years after replanting at *P. radiata* sites in the Lower South East of South Australia.

Our data suggest that after harvesting the previous rotation, once the soil profile has re-wet sufficiently to allow unsaturated flow to begin, recharge proceeds at a rate largely determined by rainfall. For the two *P. radiata* sites, which we consider reasonably representative of typical *P. radiata* sites in the region, annual recharge correlated strongly with annual rainfall (Figure 18). This is based on the final 3 years of data at Site 1 and the final 2 years at Site 2.

Mitchell and Correll (1987) observed watertable rises of approximately 5 m in the first two winter-spring periods after planting in first and second rotation *P. radiata* plantations in Tantanoola State Forest near Glencoe, SA, for rainfall averaging 903 mm year^{-1} in these two years. Using the Brown *et al*. (2006) watertable fluctuation method and assuming a specific yield of 10%, a 5 m rise in the watertable indicates ~500 mm year^{-1} groundwater recharge. For comparison, applying the regression relationship in Figure 18 to rainfall of 903 mm, gives estimated recharge of 515 mm year^{-1}. Therefore, our estimates of recharge in the first 2 years after replanting *P. radiata* plantations are consistent with the watertable fluctuations observed by Mitchell and Correll (1987). It is important to note however, that we do not know the specific yield of the shallow aquifer at the Mitchell and Correll sites.

We measured changes in soil water to a maximum depth of 5.8 m, which was either to the watertable, or to the depth of limestone that was too hard to install access tubes any deeper. The soil water balance at Site 2 indicated the mature plantation may have accessed water from deeper than 5.8 m in the summer and autumn prior to harvesting of the plantation. This may indicate the pine tree roots extended through fractures in the limestone. It is possible that at some sites, plantations can develop a root zone deeper than 5.8 m. If this is the case, the deficit in soil water at the end of a rotation may be greater than the average we have determined based on measurements of soil water to a maximum depth of 5.8 m. The effect of this would be to reduce the amount of groundwater recharge. Our measurements of soil water from across a number of sites with >6 m depth to groundwater indicated the maximum soil water deficit at such sites averaged 57 m m^{-1} (Benyon *et al*., 2006). For each additional 1 m of root zone depth at the end of the rotation, recharge would be reduced by this amount, on average. Further investigations of maximum depth of drying would be required at sites in the region to refine the estimates of groundwater recharge in the early part of the rotation.

4.2. Comparison with previously assumed recharge rates

Current assumptions about recharge in each year of a rotation are detailed in Table 1. These are relative to the mean annual recharge rate expected for each groundwater management area estimated previously by Brown *et al*. (2006) (Table 2). These would apply for years of average rainfall. For comparison, we used the regression equation from Figure 18 to estimate recharge under average rainfall in years 2 and 3 after harvesting (year 2 only at Site 3). Year 0 is the fallow year prior to replanting, for which we have incomplete data.

As shown in Table 4, in years 2 and 3 after harvesting, recharge rates estimated from Figure 18 are substantially higher than the currently assumed rates based on Table 1 and Brown *et al*. (2006). For *P. radiata* at site 1, for annual rainfall of 681 mm, Figure 18 predicts total recharge of 676 mm in years 2 and 3 after harvesting, compared with 252 mm based on previously assumed rates. For Site 2, the comparison is 838 mm based on our data, versus 270 mm previously assumed. For *E. globulus* at Site 3, for year 2 only, the comparison is 382 mm based on Figure 18, versus 160 mm based on Table 1 and Brown *et al*. (2006).

Table 4. Estimated recharge rates in years 1 and 2 after replanting.

These are based on currently assumed rates determined from Table 1 and Brown et al. 2006 and on the regression relationship from Figure 18, assuming long-term mean annual rainfall.

Year of rotation	Site 1 681 mm MAP		Site 2 782 mm MAP		Site 3 736 mm MAP	
	Table 1	Figure 18	Table 1	Figure 18	Table 1	Figure 18
0	168	n.m.	180	n.m.	240	n.m.
1	140	338	150	419	160	382
2	112	338	120	419		

n.m. indicates we were not able to measure rainfall and ET during the first few months after harvesting.

In Table 4, we have not included an estimate of recharge in the first year after harvesting, because we did not obtain accurate measurements of rainfall and ET for several months after harvesting at each site. At Site 1, measurement of soil water only started about 5 or 6 months after harvesting, at which time it appeared the profile had already wet up sufficiently for recharge to occur. At site 2, three of the five access tubes originally used for monitoring soil water could not be found after harvesting and replacements were not installed until 9 months after harvesting. Changes in net soil water in two access tubes monitored throughout the study indicated the profile had wet up to the maximum depth of 5.8 m some time between early May and mid June 2007, about 8 months after harvesting. The volumetric water content of the soil to 5.8 m depth was 564 mm at the time measurements ceased in mid August 2006 prior to harvesting. When the first significant increase in soil water was recorded at 5.8 m depth, total soil water had increased to 764 mm. This suggests the difference between total soil water when recharge began and at the time of harvesting was <200 mm. At Site 3, rainfall and ET were not measured for almost 4.5 months during and after harvesting, and soil water was not measured for 5.5 months over this time. Two access tubes were damaged or lost during harvesting. Based on the three remaining tubes, total soil water in the 3 m above the watertable increased from 571 mm in May 2007, before harvesting, to 618 mm in November 2007 (the first measurement after harvesting) and never exceeded 624 mm in the following winter. This suggests the deficit in soil water at the time of harvesting was no more than 53 mm and that in the first winter after harvesting the soil profile had fully re-wet. From this analysis, it appears the soil water deficit at the time of harvesting was no more than 200 mm at Site 2 and no more than 53 mm at Site 3. Based on the regression from Figure 18, and assuming this deficit would need to be made up before recharge began, recharge in the fallow year, for an average rainfall year, would be 219 mm at Site 2 and 329 mm at Site 3. For comparison, recharge in the fallow year estimated based on Table 1 and Brown *et al*. (2006) is 180 mm at Site 2 and 240 mm at Site 3.

Over a 35 year rotation, for Sites 1 and 2, the additional recharge for years 2 and 3 after harvesting is equivalent to an average 14 mm year^{-1}, compared with current assumptions. For *E. globulus*, the additional recharge in year 2 equates to 20 mm year^{-1} averaged across an 11 year rotation.

The deemed recharge rates assume that for 1 year after each thinning in *P. radiata*, there is recharge equivalent to 50% of the GMA recharge rate. During a typical rotation, the plantation is thinned four times, meaning total deemed recharge equivalent to 2 years of GMA recharge. However, there are few data indicating whether and how much recharge actually occurs after thinning. Data from one site indicates there was no recharge after first thinning (Benyon *et al*. 2008), however data from another site indicated there may have been some recharge after a third thinning (CSIRO unpublished data). At the latter site, soil water was only measured to 2.4 m depth, so it is uncertain whether an excess of rainfall over evapotranspiration in the 2 years after thinning represented recharge or an accumulation of soil water deeper in the root zone.

For *E. globulus*, the deemed recharge rates are based on an assumption recharge occurs for 1 year after harvesting and then another 2 years after replanting. As our study site was not managed as typical *E. globulus* after harvesting, our data does not necessarily provide an accurate indication of recharge occurring after replanting. It is possible the recharge rate we measured in the year after harvesting also applies for the first year after re-establishment of the plantation, if this is by seedlings. The cut stumps at our study site coppiced to a height of up to 2 m in the first year after harvesting, before the coppice was killed with herbicide, indicating that if re-establishment of the plantation is by coppicing of the existing tree stumps, recharge will diminish more rapidly.

4.3. Development of a simple empirical model of groundwater recharge

To estimate the total recharge at the beginning of each rotation, recharge in the first year after harvesting needs to be estimated. This depends on soil water deficit at the time of harvesting in addition to rainfall and evapotranspiration. The soil water deficit at the time of harvesting depends on depth to groundwater and time of year. Where depth to groundwater is shallow, the plantation dries out the soil less because water is accessible from the watertable and the root zone is shallower. In early spring, the soil is not so dry because winter rainfall has recharged the profile somewhat. Soil water stores are usually the most depleted in early to mid autumn. We calculated the average soil water deficit at plantation sites with depth to groundwater >6 m and < 6 m. At sites with > 6 m depth to groundwater, the mean soil water deficit varied with time of year, from a mean maximum of 323 mm in early autumn to a mean minimum of 141 mm in early spring. The average deficit was 232 mm. At sites with <6 m depth to groundwater, the maximum soil water deficit averaged 199 mm, the minimum averaged 31 mm and the mean was 115 mm.

This means that for sites with <6 m depth to groundwater, the average deficit in soil water at the end of a rotation would be 115 mm and little recharge will occur after harvesting until this deficit has been made up. In the first year after harvest, recharge would, on average, be equal to the amount of recharge determined from Figure 18, less 115 mm. Similarly, for sites with >6 m depth to groundwater, the recharge in the first year after harvesting is equal to recharge determined from the regression in Figure 18, less 232 mm, on average.

5. CONCLUSIONS AND RECOMMENDATIONS

As has been observed previously in the Lower South East of South Australia and southwest Victoria, plantations with closed canopies use all of the rainfall and in some cases extract groundwater.

Based on observations at three field sites, after harvesting, evapotranspiration is reduced to <400 mm year^{-1} for up to 3 years at plantation sites where weeds are controlled. The soil profile refills in the first winter after harvesting, allowing substantial recharge to occur as long as the vegetation cover of weeds and small trees, remains sparse. Groundwater recharge during this period is substantially higher than previously assumed, but is consistent with watertable fluctuations observed under a young pine plantation by Mitchell and Correll (1987). For sites with <6 m depth to groundwater, these estimates do not include groundwater extraction.

Further data on ET and recharge rates for plantations aged from 2 years to canopy closure (4 to 6 years in *P. radiata* and 2 to 3 years in *E. globulus*) and after thinning in *P. radiata* need to be obtained before a full rotation, net water balance can be provided.

We recommend the following additional research be undertaken:

1. Continued monitoring of rainfall, evapotranspiration, water balances and deep drainage at the two *P. radiata* research sites used for this study, and at several additional *P. radiata* sites to confirm the findings to date and enable accurate quantification of the total recharge in the full period prior to canopy closure in this species.
2. Additional monitoring of rainfall, evapotranspiration, soil water balances and deep drainage at several representative *E. globulus* sites from planting to canopy closure to enable improved accuracy in estimates of recharge up to canopy closure in this species.
3. Controlled experiments at at least one site of each species to examine the effects on recharge of different early rotation management techniques. Replicated plots covering the typical range of variation in early rotation site management techniques, such as the intensity and duration of weed control, would provide useful data to enable more accurate estimates of groundwater recharge.
4. Monitoring of rainfall, evapotranspiration, soil water balances and deep drainage at several *P. radiata* sites for 2 to 3 years following thinning. This monitoring would need to include sites covering a range of age and productivity classes, and should employ an experimental design of replicated thinned and unthinned control plots to enable the statistical significance of any recharge to be estimated.

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