Water Resources Directorate
Surface Water Branch

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Water Authority of
Western Australia
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The Effect of Irrigation on Blue Gum (*Eucalyptus globulus*) Water Uptake : Implications for Land Disposal of Sewerage Effluent

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SUMMARY

- Due to lack of quantitative information on the water uptake of Tasmanian Blue Gum (Eucalyptus globulus) plantations, planning studies on the land disposal of Albany wastewater have had to estimate the evapotranspiration component of site water balance models. With the Albany land treatment site being in an early phase of construction, an alternative study site was chosen (Wandalup Farm near Mandurah) which had an established Blue Gum plantation adjacent to a nutrient-enriched wastewater supply (piggery effluent).

- The primary objectives of the present study were a) to measure the seasonal variability of Blue Gum water uptake under irrigated conditions and compare with rainfed trees, b) relate water uptake data with climatic variables in order to extrapolate findings from the study site to the Albany land disposal site, and c) determine the minimum annual rate of tree water use expected under irrigated conditions.

- The sapflow rates of up to nine trees were measured for 10-23 months. Three treatments each with three monitored trees were established, a) effluent-irrigated, b) water-irrigated, and c) rainfed. Groundwater levels, meteorological parameters and soil, water and foliar nutrient concentrations were also monitored.

- Lower than expected water uptake rates were observed due to the wet site conditions at Wandalup Farm. Shallow groundwater and winter waterlogging restricted root development to the top 60 cm of soil. Therefore, the tree water uptake rates under these conditions should be considered as equivalent to the lower end of the spectrum in transpiration performance expected for Albany.

- Water uptake in the irrigated treatments increased 30-40% within one week of irrigation starting. During the same period water uptake in the rainfed treatment increased 0-5%.

- On a cumulative basis, the irrigated treatments had a 44% (or 400 mm) greater total water uptake by the end of the experiment (23 months).

- The Leaf Area Index of the irrigated treatments increased gradually over the course of the experiment, whereas the rainfed treatment was either stable or decreased.

- A particularly dry summer during the experiment resulted in the death of one tree in the rainfed treatment. There was also evidence of a reduction in tree water uptake from mid-summer onwards due to soil moisture becoming limited in the rainfed treatment. The irrigated treatments maintained elevated water uptake rates throughout summer. This implies that the supply of additional water to the trees during the 'high-energy' months of the year significantly increases the magnitude and duration of elevated water use.

- During the cooler/wetter months of the year, average water uptake is 40-60% lower than summer averages. It is during this time of the year that soil moisture is no longer limiting the rate of water uptake. However, evaporative energy is limiting and irrigation during this time of the year would lead to excessive waterlogging. The differences in water uptake between the irrigated and rainfed treatments during late winter were reduced.

- Water uptake/pan evaporation ratios (WU:PE) were calculated to allow extrapolation to the Albany land disposal site given the average monthly pan evaporation data from the Albany airport. Annual PE at Albany is 207 mm lower than at Wandalup resulting in 5.7-8.2% lower estimated WU values for Albany. For effluent-irrigated trees, the annual WU at Albany, estimated from Wandalup, is 610 mm. For rainfed trees it is 377 mm. This is representative of trees growing in areas of poor drainage which would include the areas of shallow sand over clay/laterite at the Albany site. Estimates of WU extrapolated from a study at a well drained site (Marshall and Chester, 1991) suggest an annual WU of 842 mm for irrigated trees. Both of the these values are significantly lower than the estimated 1249 mm in the Planning Study for the Albany Land Treatment Site.

- The apparent overestimation of water uptake in the Planning Study is a result of having a constant WU:PE ratio of 0.93 throughout the year in the water balance model for the site. The quantitative measurements made in the present study demonstrate that the WU:PE ratio varies throughout the year ranging from 0.31 in March to 0.91 in June. Reassessment of the Albany (and future) land disposal site WU rates using the results of the present study, would result in a more accurate determination of irrigation timing, flow rates and area of plantation required to transpire estimated water loads.

CONTENTS

1.0 Introduction

Current methods of municipal sewerage disposal such as release of primary or secondary-treated effluent directly into aquatic environments, are becoming less exceptable and greater recycling of effluent is encouraged. The prevention of nutrient enrichment (eutrophication) of freshwater and marine ecosystems has received considerable attention in recent years, encouraged by public opinion and legislative pressure. Tertiary treatment to remove nutrients from effluent prior to disposal is very expensive and therefore a cheaper means of effluent disposal that is more environmentally acceptable is required.

A commonly preferred option is land disposal of effluent. This is usually in the form of flood irrigation of pasture, spray irrigation of parks and recreation areas, irrigation of horticultural crops, and more recently, irrigation of wood or pulpwood plantations (woodlots). In Australia, the irrigation of woodlots with effluent is favoured over other methods of land disposal for several reasons (Stewart et al., 1986; Allender, 1988):

- higher rate of water use than horticultural crops
- less intensive management
- lower health risks as toxic components of effluent do not enter the food chain.

Although there is a number of irrigated woodlots in Australia, there is still a paucity of information widely available on their water use and nutrient uptake/retention. Myers (1992) stresses that in order to evaluate the feasibility of effluent irrigation of woodlots at a particular site, information is required on the following:

- physical and chemical properties of the soil
- effluent characteristics
- climate
- expected growth and water use rates of trees

Information on soil and effluent properties is necessary to determine the suitability of soils for irrigation with a particular effluent. Nutrients must be retained in the surface soils or exported from the site in the form of biomass. Therefore the soils must have the capacity to retain nutrients, particularly phosphorus, preventing both leaching through to the groundwater and excessive runoff. The climate and biological characteristics of the woodlot determine the water balance and in particular the effluent loading rates and the amount of land required to dispose of a given amount of effluent.

The Water Authority of Western Australia is developing a land disposal site near Albany, irrigating Blue Gum (*Eucalyptus globulus* ssp *globulus*) plantations with secondary treated municipal effluent with the intent of harvesting the trees for paper pulp production. An extensive preliminary planning study for the project (WAWA, 1991, 1992) highlighted the scarcity of existing information on irrigated woodlot water balances, particularly the rate of tree water use. A preliminary 1 month study of the water use of irrigated *E. globulus* (Marshall and Chester, 1991) corrected initial over-estimations of water use for the site, but did not provide sufficient data for a hydrological assessment over a full seasonal cycle. Such information is necessary for the development of an accurate model of the water balance of the disposal site. This report aims to provide information on the water use of irrigated *E. globulus* required for future modelling of a site water balance. The principal objectives are:

- Determine the variability in water use over a full seasonal cycle
- Compare the water use and growth of effluent-irrigated, groundwater-irrigated and rainfed trees
- Establish the relationship between water use and climatic factors to allow extrapolation to other sites in the south west of Western Australia
- Estimate the minimum rate of tree water use expected under irrigated conditions.

2.0 Study Site Description

The experiment was located at Wandalup Farm, a commercial piggery located 10 km east of Mandurah (Fig. 1). The site was chosen on the basis of having an established plantation (150 ha) of *E. globulus* adjacent to a ready supply of nutrient-rich effluent. An effluent pond was located within 100 m of the plantation allowing a gravity-fed irrigation system to be constructed at low cost.

The plantation was established by the Department of Conservation and Land Management during 1989. Trees were planted in a 'tramline' arrangement; a pair of parallel rows approximately 3.4 m apart, adjacent pairs spaced approximately 5.4 m apart. Trees within a row were spaced 2.5 m apart. Each row was mounded to 30 cm prior to planting.

The landscape position of the plantation was at the bottom of a very broad, shallow valley, adjacent to a drain which runs through the property. Soils at the site are typically grey, course sand over a confining layer of coffee rock at 1-1.5 m depth. Judging from the original vegetation of scattered *Melaleuca preissiana, Astartea fascicularis and Juncus pallidus*, the site was classed as relatively wet. Surface water ponding and shallow groundwater levels support this inference. The landscape position was considered analogous to areas of the Albany Land Disposal Site which may be subject to winter

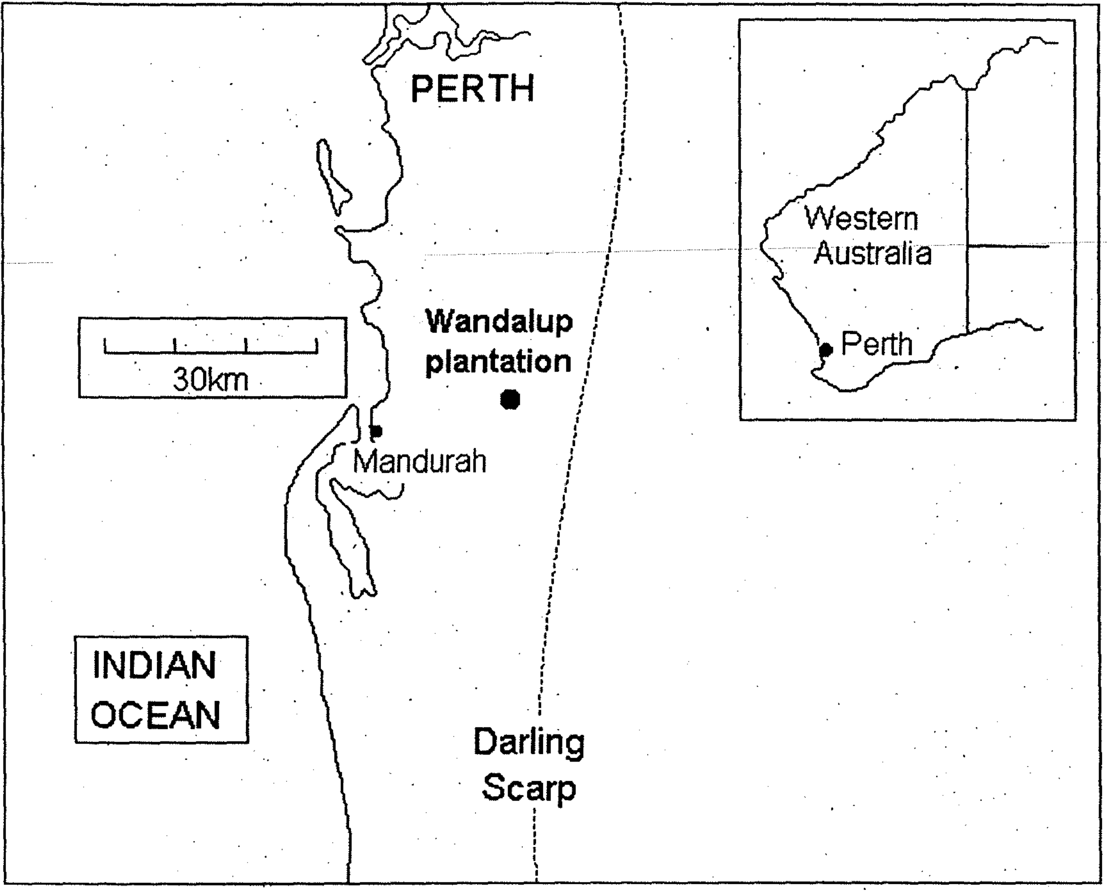

Figure 1: Location of the Wandalup Farm plantation relative to Mandurah and Perth. The Darling Scarp represents the eastern limit of the Swan Coastal Plain.

waterlogging or perched shallow groundwater levels. Therefore, water uptake of the trees at Wandalup Farm may be comparable to the water uptake of trees positioned at the 'worst' areas of the Albany site.

3.0 Methods

3.1 Experimental Design and Irrigation

Within a 1 ha area of the plantation and adjacent to the effluent pond, 3 pairs of rows were selected and a block of twenty trees in each pair was tagged. Each of the three blocks represented a different experimental treatment, effluent-irrigated, groundwater-irrigated and rainfed. All trees within each block was measured for diameter over bark at breast height (DBH) and a tree with a DBH closest to the average was selected from each block as the tree for continuous water use measurement. These three trees were recorded as the Effluent Tree (ET), Water Tree (WT) and the Rain-fed Tree (RT). At a latter date in the experiment (see section 3.2 below) two additional trees (one either side of the ET, WT and RT) within each treatment block were also continuously measured for water uptake. These additional trees were recorded as Effluent Tree East and West (ETE and ETW), Water Tree East and West (WTE and WTW) and Rain-fed Tree East and West (RTE and RTW).

A 50 mm polypropylene pipe was used to transfer effluent from the storage pond to the effluent-irrigated treatment block. The effluent was gravity fed with a maximum static head of approximately 5 m. At the effluent-irrigated treatment block the effluent was initially delivered via adjustable drip emitters (four per tree) from 20mm polypropylene pipe encircling the base of each tree (ET, ETE, ETW). The low delivery pressure and suspended sediments did not allow the drip emitters to function at their rated output or without blockage, despite the use of inline filters. Therefore it was necessary to remove the emitters entirely and allow the irrigation to flow from the resulting holes (4mm diameter) in the 20 mm pipe while relying on gate valves to set the rate of delivery.

Dilution was necessary as the concentrations of total nitrogen and phosphorus in the piggery effluent were too high to use for irrigation if toxic effects on the trees were to be avoided. Secondly, it was decided to dilute the effluent to simulate nutrient concentrations in secondary treated human effluent, for comparison with the irrigated woodlots proposed for Albany. Based on the differences in average nutrient concentrations of the two types of effluent, a 1:4 dilution was achieved by mixing the effluent with bore water as it was applied to the trees.

Bore water for the water-irrigated treatment block was sourced from a nearby tank kept full by a float valve and pump and was applied to the trees (WT, WTE, WTW) in the same way as the effluent-irrigated treatment.

Although the problem with dripper blockage was overcome, irrigation rates for both treatments were not consistent due to sporadic blockage of the inline filters and holes in the pipe. However, the average irrigation rate was estimated to be 100 litres per tree per day. This equates to the calculated maximum replacement rate of 110 litres per day (maximum daily evaporation less rainfall x area per tree, ie. 10mm x 11 m2). This rate also compares favourably with the estimated loading rates per tree for the Albany land disposal site (WAWA, 1992). Trees in the rainfed treatment block were not irrigated.

The first irrigation period commenced during January 1993, after 7 months of pre-treatment water uptake measurements, and finished during early June 1993. The second irrigation period commenced during early November 1993 and ended in July 1994.

3.2 Water Uptake Measurement

The water uptake was measured using Custom Heat Pulse Loggers (Department of Scientific and Industrial Research, Soil Conservation Service, Aokautere, New Zealand). The sapflow velocity vs depth into sapwood relationship was determined using the methods outlined by Marshall (1992), for each tree selected for measurement. Probe positions and depths were then set accordingly. Water uptake measurements of the ET, WT and RT commenced on 4 June 1992. Measurements were made using one heat pulse logger per tree until 20 July 1993 when water uptake of ETE, ETW, WTE, WTW, RTE and RTW was also measured. A single logger was then used to measure the water uptake within each group of three trees (single probe in each of the east and west trees and the remaining two probes in the central tree). Sapflow readings were taken every 20 minutes until the end of the experiment on 25 April 1994. All water uptake values were initially expressed as either litres per day (litres d^{-1}) or mm per day (mm d^{-1}).

It is appropriate to mention here the limitations in the experimental design which are imposed by the method of water use measurement employed. The cost and design of the heat pulse units limits their use to one tree per logger if all 4 probe pairs are used on the one tree. Although this technique gives the most accurate measurements of water use, it restricts the number of individuals measured within each treatment. It is for this reason that the technique was modified to monitor three trees with one logger as described in and Appendix 2.

3.3 Leaf Area Measurements

Leaf area of the monitored trees was measured using the Marshall-Chester Griding Technique which is explained in detail in Appendix 1a. Leaf area measurement was not initially part of the study at Wandalup Farm, therefore "Day 1" leaf areas were later estimated by developing a relationship between diameter over bark and leaf area from measurements on an extended sample of trees (Appendix

1b). This result was then used to estimate the leaf area of each study tree from their original diameters recorded at the start of the experiment.

Measurements were estimated for the start of the experiment (June 1992), and measured one year later (July 1993), during the following summer (December 1993) and at the end of the experiment (July 1994). Measurements of the trees east and west of the continuously monitored trees were not made in June 1992. At the end of the study, three (ETE, WT and RTW) of the nine trees were measured destructively to verify the accuracy of the earlier measurements.

3.4 Meteorological Measurements

A automatic meteorological station measuring air temperature, humidity, net solar radiation, wind speed, rainfall and class A pan evaporation was established adjacent to the experimental site. The evaporation pan was re-filled each week but the level in the pan was monitored with a float sensor to automatically provide daily changes of level and hence evaporation (Unidata Australia, modified Model 6531 Water Level Instrument).

Errors in the pan evaporation data were corrected as described by Marshall and Chester (1992) using evaporation data from Perth Airport and Wokalup Agricultural Research Station.

3.5 Groundwater Monitoring

A piezometer (50mm class 9 slotted PVC tube, capped) was installed in each of the treatment blocks, adjacent to the trees monitored for water uptake. Maximum depth of each piezometer was 1.5 m. Depth to groundwater was measured each month for the duration of the experiment.

Gravimetric soil moisture was measured monthly for the last seven months of the study. This involved extracting a known volume of soil from a hole freshly dug each month at a depth half way to groundwater within the area of irrigation effect. The average soil moisture content of each treatment was obtained by measuring fresh and oven dry weights of three samples.

3.6 Nutrient Analyses

NO_3-N, NO_2-N, NH_4-N and PO_4-P were analysed from bore water, groundwater and effluent samples taken at two dates during the experiment (December '93 and March '94). Live leaf material was also sampled on the same dates for total P and total N analysis (Appendix 2). Bore water, used to irrigate the water treatment trees, was sampled at the point of dispersal. Groundwater (three samples) was sampled from the piezometer in each treatment. Effluent was sampled before dilution at the effluent-irrigated treatment only.

3.7 Extrapolation of Results to Albany

The primary yardstick for sufficient transpiration, when determining the success of irrigated woodlots, is the level of available radiation, and hence evaporation, coupled with the amount and pattern of rainfall. Water uptake (WU) at Wandalup was therefore modelled against pan evaporation (PE) to determine the WU:PE ratio on a monthly basis. This ratio was then used to derive monthly WU at Albany from the PE recorded by the Bureau of Meteorology to compare with the WU predicted for Albany in the Planning Study (WAWA, 1992).

4.0 Results

4.1 Seasonal Trends in Water Uptake and Comparisons between Treatments

Only the ET, WT and RT were measured for water uptake over the full 23 months of the experiment. It is from these trees in particular therefore that the influence of two full seasonal cycles on trends in water uptake are most evident.

All three trees displayed seasonal variation in water uptake, the variation being greater in the ET and WT (Fig. 2). The ranges in water uptake (WU) in mm d^{-1} for the ET, WT and RT are 0.1 - 4.2, 0.25 - 3.4 and 0.0 - 2.9 respectively. Peak WU occurred during January and February in 1993 for the two irrigated trees (ET and WT) whereas in the RT elevated WU occurred over a protracted period from November 1992 to February 1993. During the second summer, elevated WU values were slightly lower and more protracted (Nov - Feb) for all three trees.

Lowest WU values typically occurred during the late autumn and winter months in all three trees with little difference between trees. For the irrigated trees, the winter WU minimums after both irrigation periods were not greatly different from the winter WU values prior to irrigation. The average winter WU of the irrigated trees was only 40-50% of their average summer WU. Winter WU of the RT was 50-60% of summer values.

In the irrigated treatments, WU increased sharply once irrigation commenced. Both the ET and WT showed increases in WU of between 30 and 40% within a week after irrigation commenced. During the same period, the RT displayed negligible (0-5%) increase in WU. During the first summer, WU of the RT started to decrease in January compared with March for the ET and WT. This suggests water is becoming limited from mid-summer in the RT treatment.

When expressed on a cumulative basis (Fig. 3), the total WU of the RT was significantly different from the two irrigated trees at the end of the 23 month experiment. The ET and WT had a 44% (or approximately 400 mm) greater cumulative WU than the RT. The difference in WU between the RT

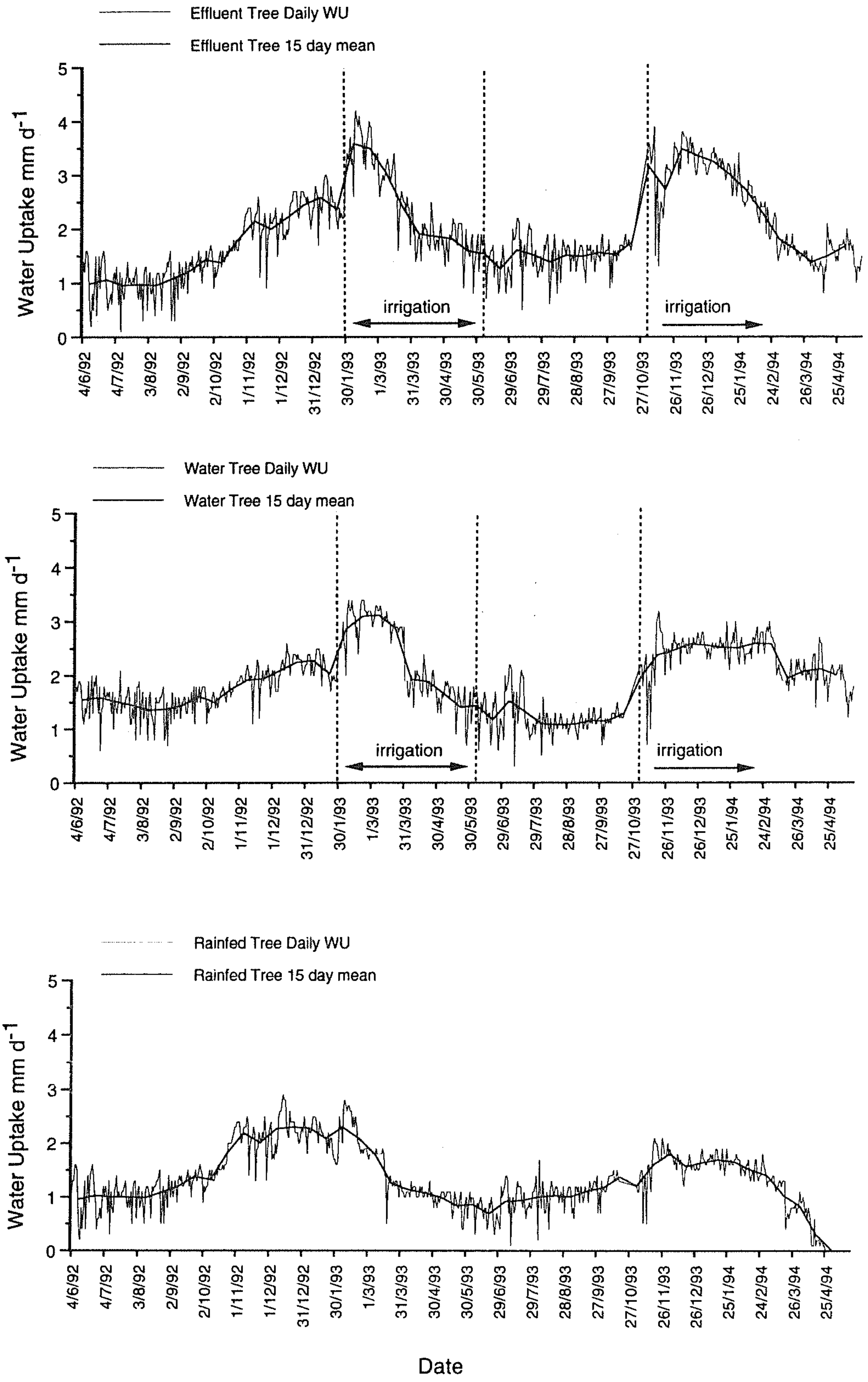

Figure 2: Daily water uptake (mm) and 15 day moving average of the effluent-irrigated tree, water-irrigated tree and rainfed tree. The periods of irrigation are also noted.

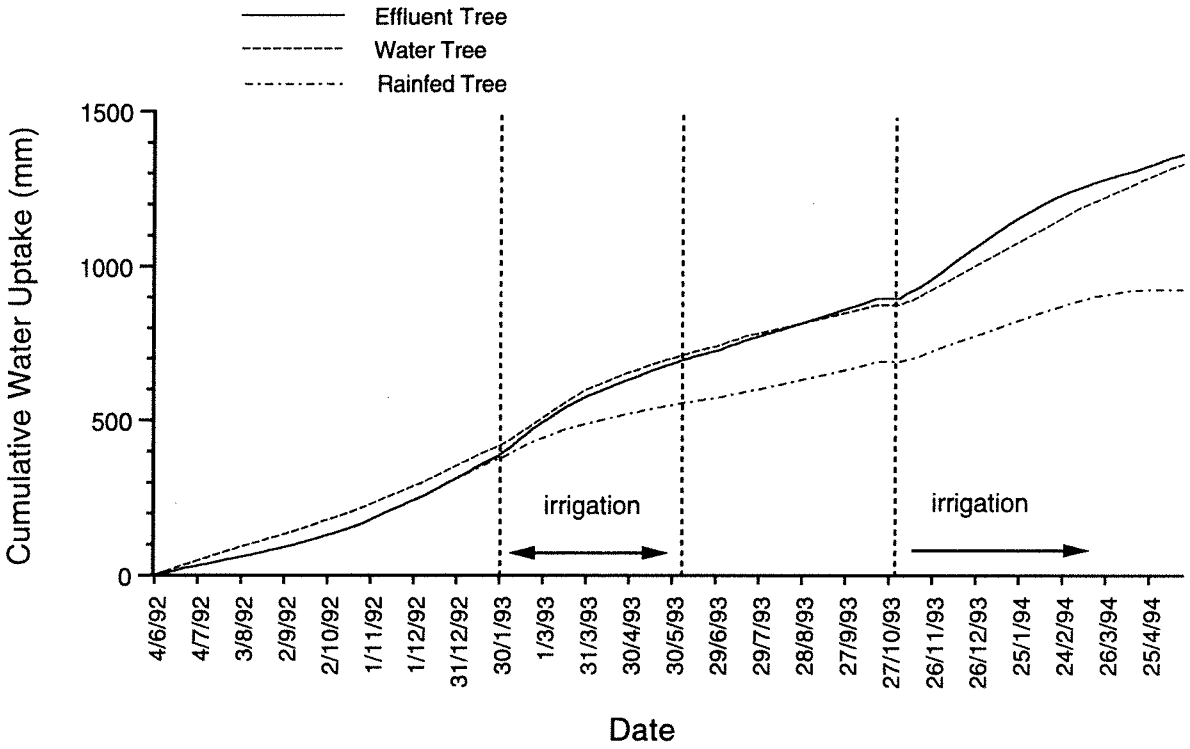

Figure 3: Cumulative water uptake (mm) over the course of the experiment for the effluent tree, water tree and rainfed tree. The periods of irrigation are also noted.

and the irrigated trees is apparent soon after the first irrigation commencement date, and the difference increased gradually during the remainder of the experiment.

Incorporating the replicate trees ETE, ETW, WTE, WTW, RTE and RTW, provides a better basis for comparisons between the three treatments. Although the replicate trees were monitored for a shorter period of time (last 10 months of the experiment), a near-complete seasonal cycle in WU is apparent (Fig. 4). All three effluent-irrigated trees (ET, ETE, ETW) and water-irrigated trees (WT, WTE, WTW) responded to irrigation by increasing WU. This is in contrast to the rainfed trees (RT, RTE, RTW) which displayed a negligible increase in WU during the corresponding period. The three effluent-irrigated trees showed negligible difference in WU after irrigation commenced. Prior to irrigation, ETW had significantly lower WU than ETE and ET. Of the water-irrigated trees WTW had lower WU than the other two trees, even after irrigation commenced. Of the rainfed trees, WU of RT was consistently higher than the other rainfed trees until the end of the experiment when its WU dropped dramatically and the tree died.

Examining the cumulative WU of the three trees in each treatment (Fig. 5) shows greater rates of increase in total WU in the irrigated treatments compared with the rainfed trees. Also of particular note is the greater variation in total WU between the rainfed trees compared with the irrigated treatments.

Plotting the mean monthly WU for each treatment (average of the three trees in each treatment) suggests there is no significant difference between the monthly values of the irrigated treatments (Fig. 6). However, the average monthly WU for the rainfed treatment is different from the irrigated treatments. This was verified by statistically testing the difference between treatments (two way ANOVA, Fisher's post-hoc test). The effluent-irrigated ($p<0.001$) and the water-irrigated ($p<0.001$) treatments were significantly different from the rainfed treatment over the 10 month period. The difference between the two irrigated treatments was not significant. The test also verified a significant within-treatment variation in WU over the 10 months (ie seasonal variation).

4.2 Water Uptake Relative to Leaf Area

Leaf area varied considerably between treatments over the length of the experiment (Fig. 7). The leaf area index (LAI) of the irrigated trees increased gradually over time, whereas the rainfed trees had either stable or decreasing LAI's. The LAI of the rainfed trees was also significantly lower than the irrigated treatments by the end of the experiment, despite having equivalent LAI's at the start of the experiment. There was no apparent difference in final LAI between the effluent-irrigated and the water-irrigated treatments.

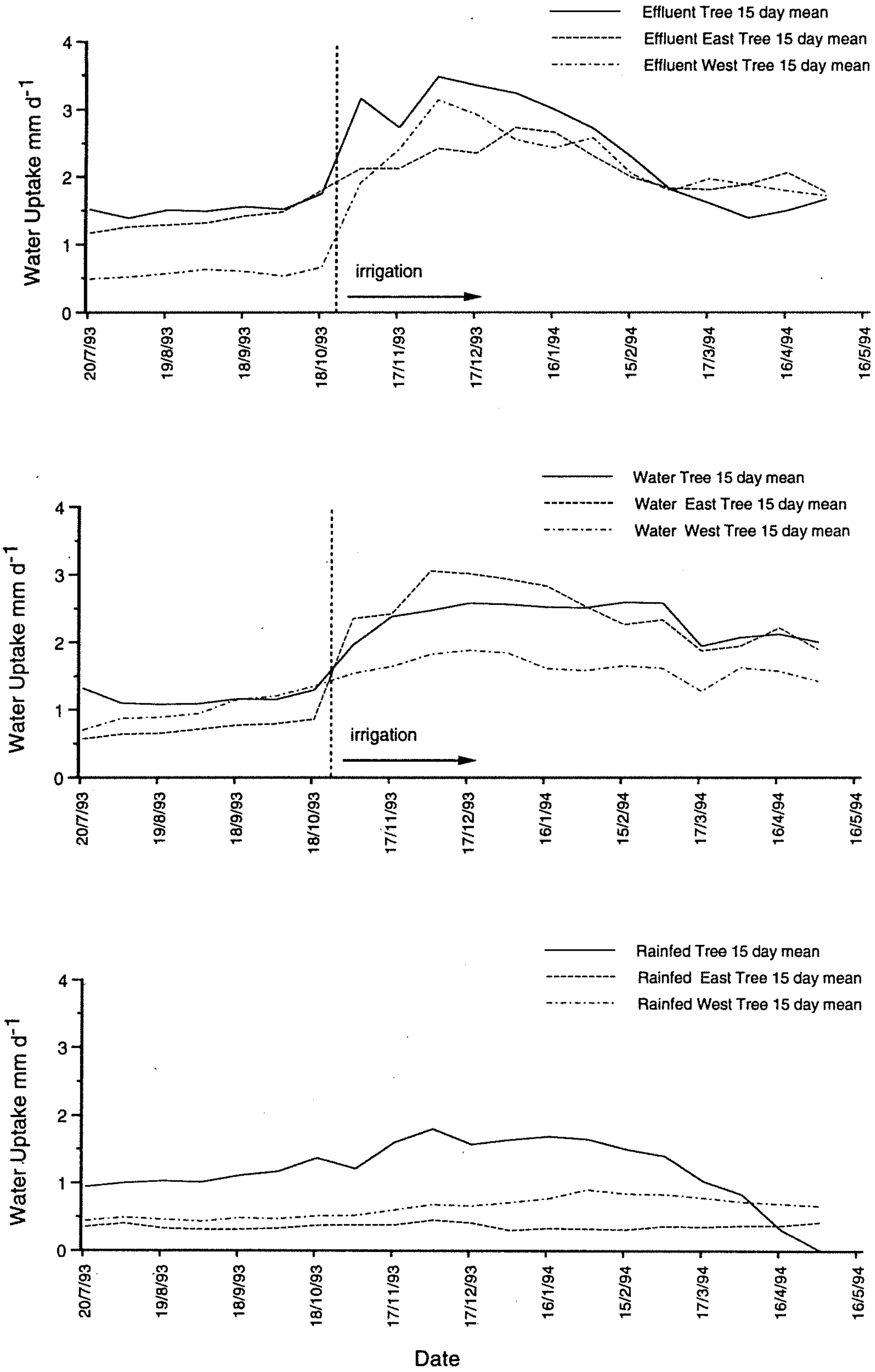

Figure 4: Daily water uptake (mm) by the effluent tree, water tree and rainfedtree and all east and west supplementary trees during the last 10 months of the experiment.

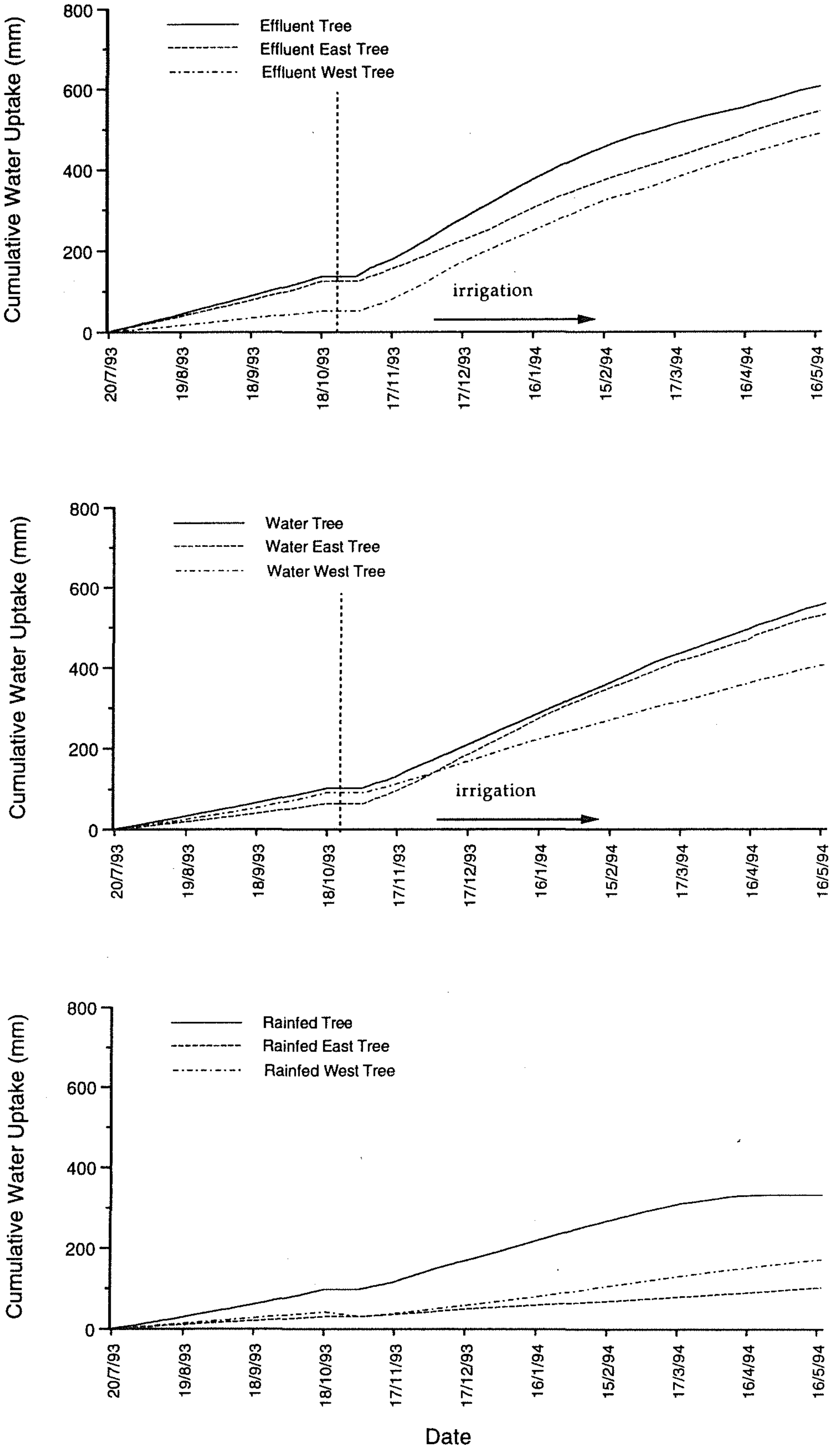

Figure 5: Cumulative water uptake (mm) by the effluent tree, water tree and rainfed tree and all east and west supplementay trees during the last 10 months of the experiment.

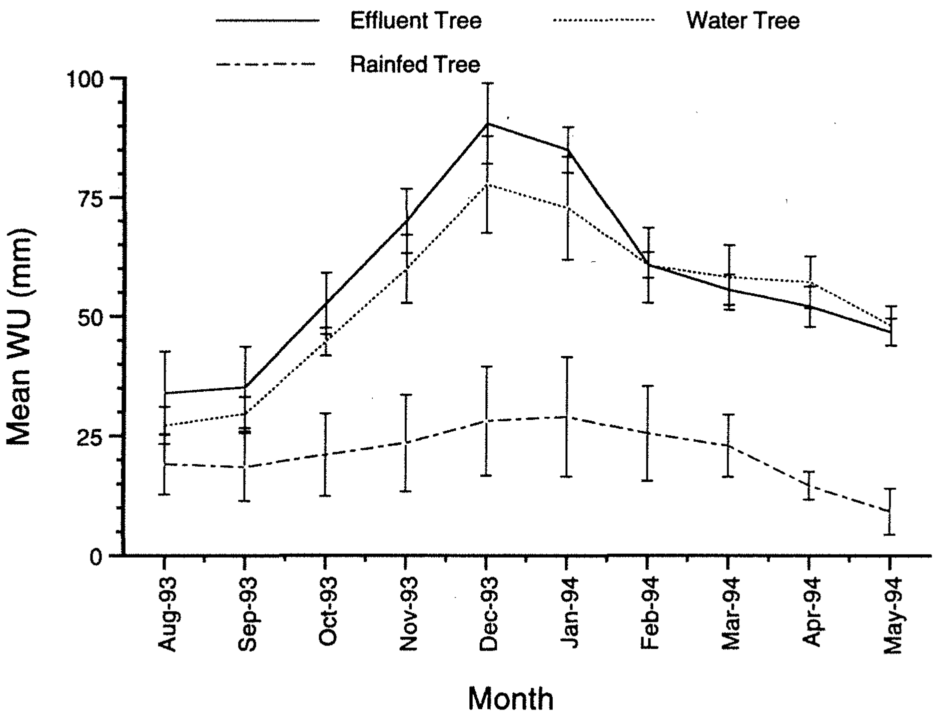

Figure 6: Mean (of centre, east and west trees) monthly water uptake (WU, mm) ± SE for the effluent, water and rainfedtreatments over the last 10 months of the experiment.

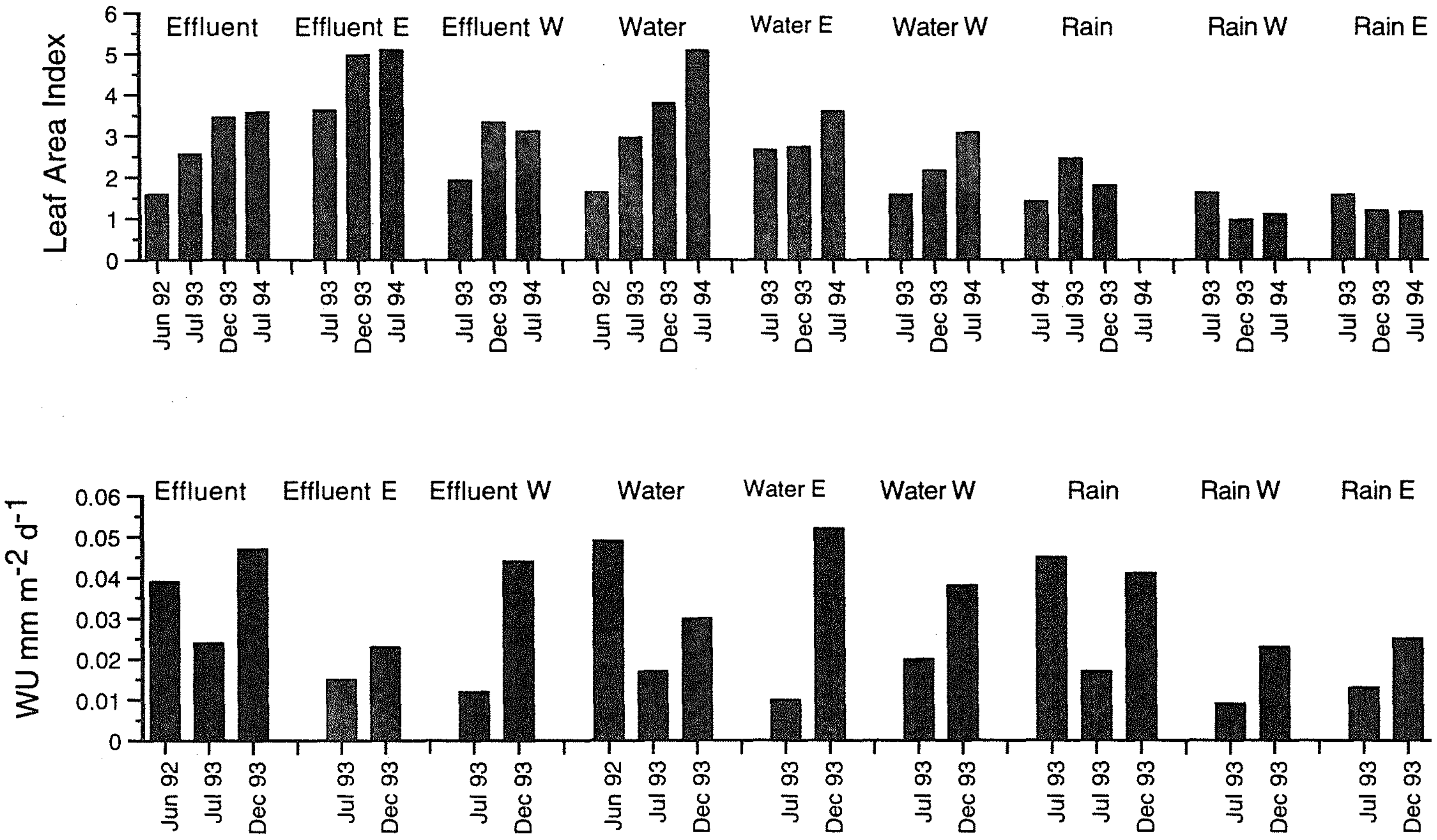

Figure 7: Leaf area index and water uptake per m^2 leaf area per day for the effluent tree, water tree, rainfed tree and all supplementary (east and west) trees at different times during the course of the experiment.

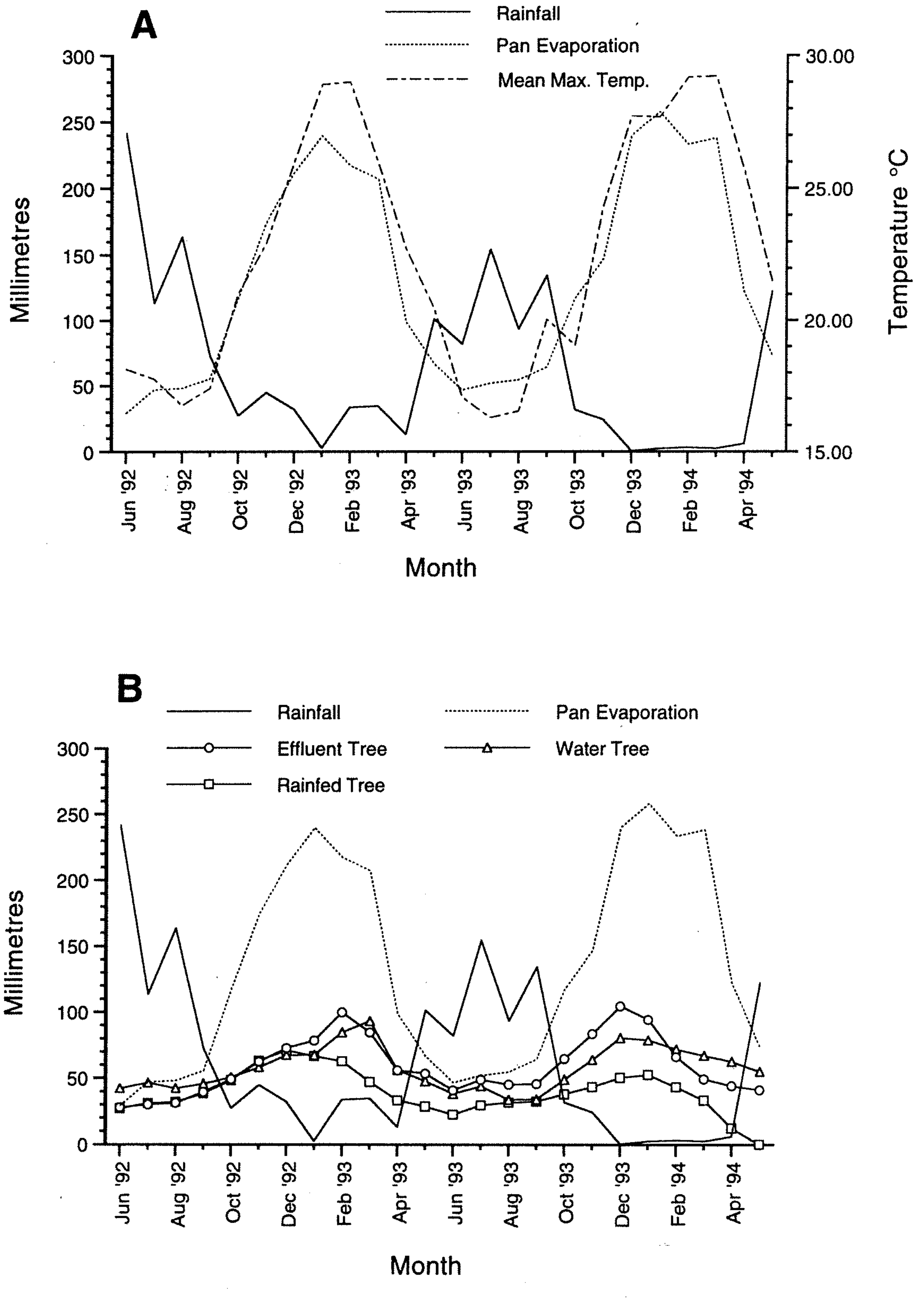

Figure 8: A) Monthly rainfall (mm), pan evaporation (mm) and mean maximum temperature (°C) at Wandalup Farm during the course of the experiment, and B) Monthly rainfall, pan evaporation and effluent tree, water tree and rainfed tree water uptake (mm) during the course of the experiment.

When expressed on a per unit area of leaf basis (WU mm m^{-2} d^{-1}), WU 'efficiency' was very variable between dates, within treatments and between treatments (Fig. 7). Low and high values were evident in all three treatments with no clear trends.

4.3 Relationship between Water Uptake and Climate: Extrapolation to Albany

Meteorological measurements taken on site during the experiment showed a typical mediterranean pattern in rainfall, maximum temperature and pan evaporation (Fig. 8). Rainfall was highest during the winter months of June, July and August. Of particular note is the lack of rainfall during the second summer (93/94) compared with the first (92/93). Pan evaporation was highest during the summer months and far exceeded rainfall.

Groundwater depths and soil moisture results reflected the rainfall patterns during the experiment (Fig. 9). During the first summer, depth to groundwater increased to approximately 1.0 m in all treatments. Depth to groundwater decreased to approximately 0.25 m during the subsequent winter, and then increased again to 1.3 m the following summer. Of particular note is the rapid decrease in depth to groundwater in response to the first rains after the very dry summer of '93/'94.

In comparing rainfall and pan evaporation to tree WU (Fig. 8), it is evident that WU was lowest when rainfall was highest (during winter), and highest during the drier and warmer summer months. Except during the winter months, pan evaporation far exceeded tree WU. Also of note is the death of the RT at the end of the particularly dry summer of 93/94.

The WU/Pan Evaporation (PE) ratio was calculated for each month during the experiment to indicate the overall WU efficiency of the trees in each treatment relative to pan evaporation. The ratio is highest in all treatments during the winter months (Fig. 10) although this apparent high 'efficiency' does not imply high WU values as pan evaporation drops dramatically relative to WU. The ratio was lowest, typically less than 0.5, during the summer months when pan evaporation was highest. During the first spring and early summer just prior to irrigation the ratio was identical for all treatments (ET, WT and RT). After irrigation commenced, there was a distinct separation between the increasing ratios of the irrigated treatments and the decreasing ratio of the rainfed tree during the high evaporation, late summer months. As winter approached ('93), the ratio of all trees increased but there was still a distinct difference between the irrigated treatment and the RT. During late winter, this difference between treatments decreased but increased again once the second irrigation period commenced. Unlike the response to the first irrigation period, the ratios of both irrigated treatments continued to fall until the beginning of autumn ('94). This is most likely in response to the very protracted, dry summer which resulted in the death of the RT. The ratios of the irrigated treatments increased dramatically after the break of season when pan evaporation dropped.

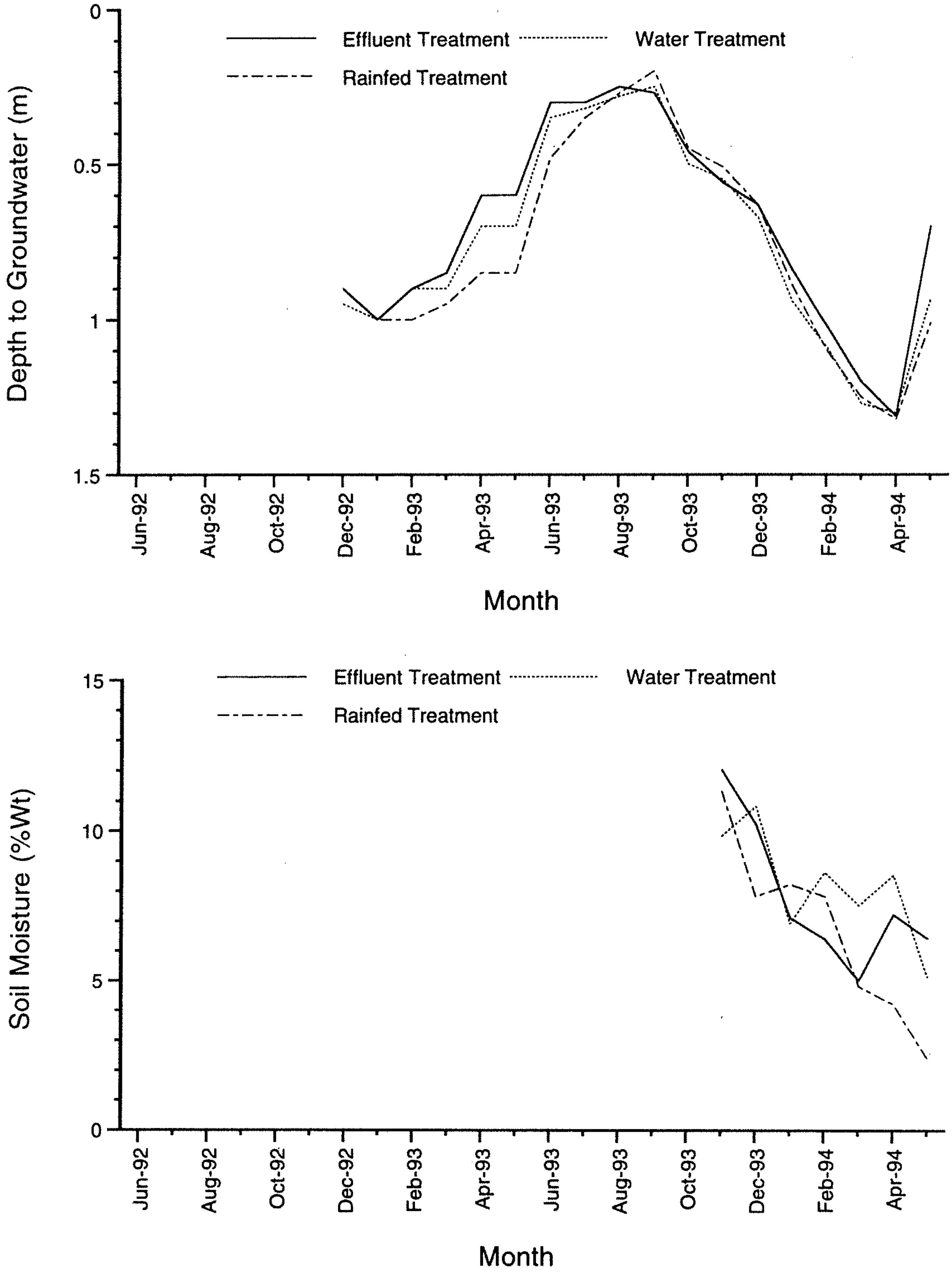

Figure 9: Depth to groundwater (m) and soil moisture (%wt) at the effluent, water and rainfed treatments during the period of the experiment when measurements were taken.

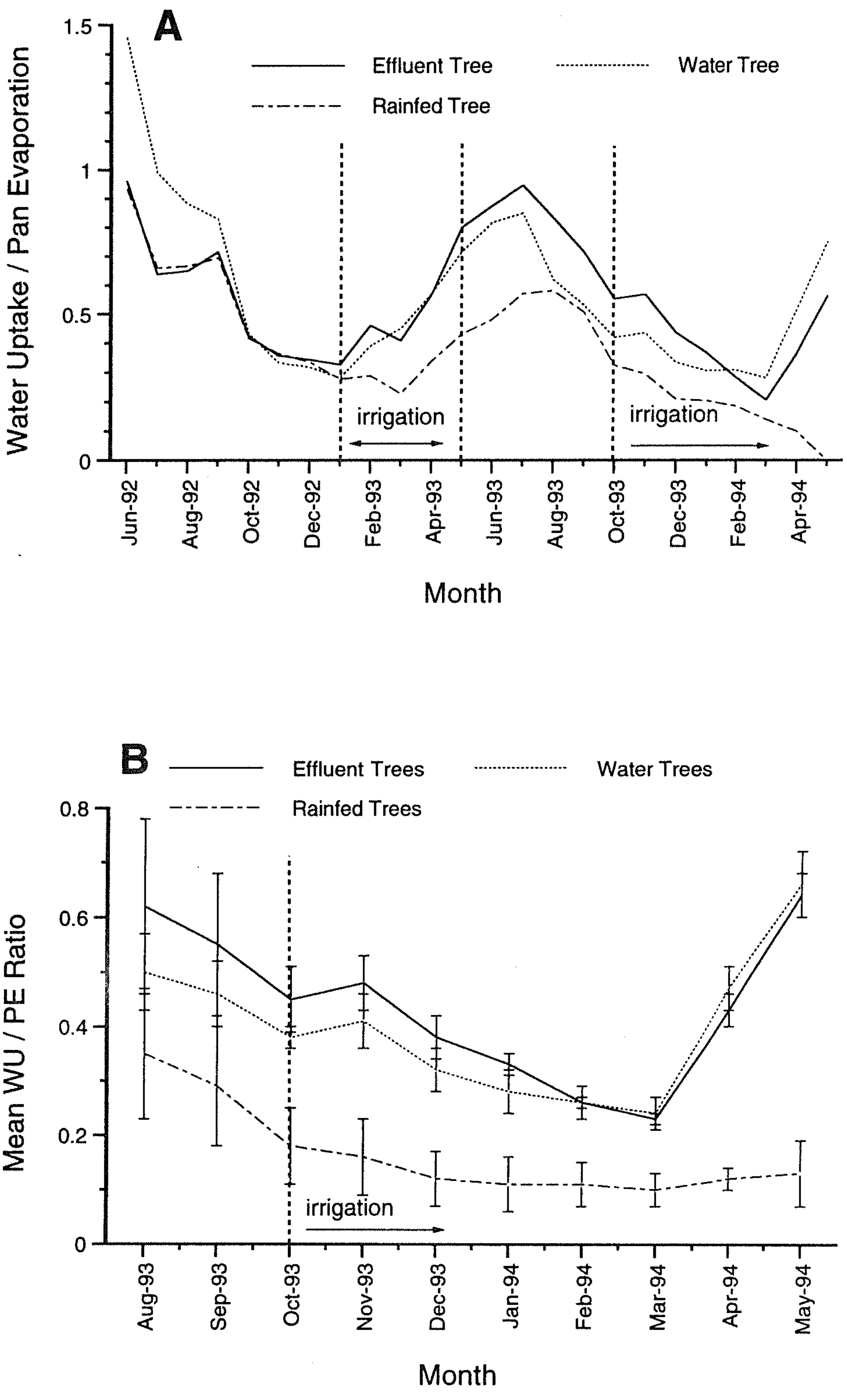

Figure 10: A) Monthly water uptake/pan evaporation ratio (WU:PE)for the effluent tree, water tree and rainfed tree over the course of the experiment, and B) Mean (of centre, east and west trees) ± SE WU:PE ratio for the effluent, water and rainfed treatments during the last 10 months of the experiment.

During the last ten months of the experiment, WU/PE ratios were determined for all the replicate trees within each treatment. At the beginning of this period there was little difference in the ratios between treatments, however, as summer approached and irrigation commenced, the ratios of the irrigated treatments increased relative to the rainfed treatment. After the particularly dry summer, once rainfall began (and irrigation continued), the ratios of the irrigated treatments increased dramatically whereas the ratios of the rainfed treatment remained significantly lower. This indicates that although there was sufficient radiant energy to increase transpiration in response to rainfall, the rainfed trees were still under significant water stress and were unable to respond as rapidly. This is also evident during the previous winter. Over the 10 month period, there was no significant difference in WU/PE between the two irrigated treatments.

Given the observed relationships between tree WU and PE, it is possible to extrapolate this relationship to Albany, the location of the land disposal site, using PE data from the Albany airport (Table 1). This analysis predicts a 5.7 - 8.2% lower annual WU of trees at Albany compared with Wandalup. Annual WU of the rainfed trees at Albany is likely to be about 61% of the effluent-irrigated trees at Albany. The seasonal patterns of PE for Wandalup and Albany were similar, however, summer PE at Wandalup was significantly higher. This needs to be taken into consideration when extrapolating the results to Albany. Greater water stress in rainfed trees during summer is likely to occur at Wandalup, therefore irrigation of trees during summer at Wandalup is likely to result in a greater percentage increase in WU relative to rainfed trees. This difference is unlikely to be so pronounced at Albany.

4.4 Foliar Tissue and Site Nutrient Concentrations

The complete results of the foliar nutrient assessment are presented in Appendix 2. Comparisons in foliar total nitrogen (TN) and total phosphorus (TP) between the treatments yielded no significant difference between the three treatments. There was also no observable trends in nutrient concentrations over the duration of the experiment. Foliar TN concentrations were between 10,000 and 14,000 μg/g, whereas TP concentrations were 1,700 to 5,735 μg/g.

The total amount of nitrogen and phosphorus within the canopy of the experimental trees was calculated using the leaf area and leaf weight results (Appendix 2). Given the lack of any significant difference in foliar nutrient concentrations between treatments, there was no attributable trends in total foliar nutrient loads. As expected, nutrient loads per tree did increase with increasing leaf area. Nitrogen loads ranged from 38.9 to 189.7 g/tree and phosphorus loads ranged from 8.7 to 42.5 g/tree.

Soil water nutrient concentrations sampled from the observation bores (groundwater) varied between treatments (Table 2). Concentrations in the effluent treatment were significantly higher than the water treatment. However, the rainfed treatment, although lower in nutrient concentration than the effluent treatment, had higher concentrations than the water treatment. There was negligible

Table 1: Average monthly pan evaporation (PE), average monthly tree water use (WU), WU/PE ratio and extrapolation of WU results to Albany.

	Pan Evaporation (PE mm)		Wandalup Water Uptake (WU mm)			Wandalup WU/PE			Estimated Albany Water Uptake (mm)		
	Wandalup*	Albany+	Effluent	Borewater	Rain	Effluent	Borewater	Rain	Effluent	Borewater	Rain
January	248	208	81.6	70.0	47.7	0.33	0.28	0.19	68.6	58.2	39.5
February	225	171	80.2	72.5	44.0	0.36	0.32	0.20	61.6	54.7	34.2
March	222	149	69.9	75.5	35.0	0.31	0.34	0.16	46.2	50.7	23.8
April	110	96	53.8	56.6	23.9	0.49	0.51	0.22	47.0	49.0	21.1
May	70	68	50.0	47.9	18.9	0.71	0.68	0.27	48.3	46.2	18.4
June	38	54	34.4	40.2	24.7	0.91	1.06	0.65	49.1	57.2	35.1
July	49	56	26.5	33.2	22.0	0.54	0.68	0.45	30.2	38.1	25.2
August	51	65	32.6	34.8	25.5	0.64	0.68	0.50	41.6	44.2	32.5
September	60	81	37.3	37.7	28.5	0.62	0.63	0.48	50.2	51.0	38.9
October	117	109	50.9	47.6	34.8	0.44	0.41	0.30	48.0	44.7	32.7
November	160	132	66.1	58.9	43.3	0.41	0.37	0.27	54.1	48.8	35.6
December	226	180	81.5	72.5	49.5	0.36	0.32	0.22	64.8	57.6	39.6
Annual Total	1576	1369	664.8	647.4	397.8				609.7	600.4	376.6
Monthly Mean	131	114	55.4	54.0	33.2	0.5	0.5	0.3	50.8	50.0	31.4

* 2 year average

\+ long term average

Table 2: Nutrient concentrations in groundwater, bore water and effluent.

Sample Material	Treatment	Date	NO3-N mg/l	NO2-N mg/l	NH4-N mg/l	PO4-P mg/l
Groundwater[1]	Effluent	Dec-93	1.27	0.03	15.60	22.00
	Water		0.06	0.00	0.02	0.17
	Rainfed		0.28	0.13	23.80	6.58
	Effluent	Mar-94	16.10	0.22	22.20	26.00
	Water		0.66	0.01	0.46	0.86
	Rainfed		0.04	0.05	31.30	1.18
Bore Water[2]		Dec-93	0.71	<0.001	0.01	0.01
		Mar-94	0.09	0.01	0.19	0.01
Effluent[3]		Dec-93	25.20	1.70	184.00	19.90
		Mar-94	0.11	0.06	176.00	3.91

1: Groundwater sampled from observation bores within each treatment

2: Bore water used to irrigated the Water Treatment

3: Effluent used to irrigate Effluent Treatment, before dilution difference between the two sample dates. The bore water used to irrigate the water treatment with had extremely low nutrient concentrations. The effluent, before dilution with bore water (4 water: 1 effluent), had very high nutrient concentrations, particularly in NH4-N.

5.0 Discussion

5.1 The Effect of Irrigation on Water Uptake

The site conditions at Wandalup Farms are less than ideal for plantation *E. globulus*, particularly if the trees are to be irrigated with nutrient-rich effluent. The sandy, shallow soil profile above a confining layer of coffee rock promotes the formation of a shallow perched groundwater level throughout the year. As a consequence, trees planted in the low-lying areas of the landscape are prone to waterlogging stress during winter and spring and, due to anoxia-induced root damage, drought stress during summer and autumn. The soil profile at Albany is typically duplex with a shallow sandy top horizon and a restricting layer of clay/laterite at a depth between 0.4 - 1.5 m. During winter and spring, the low-lying sites are likely to become waterlogged, leading to a similar scenario as Wandalup. Tree water use at those sites prone to waterlogging is expected to be lower than trees growing on deeper soil profiles, and consequently represent the lower end of the range in transpiration. The results extrapolated from Wandalup therefore, should be viewed as being representative of the minimum water uptake performance at Albany.

The spring and summer irrigation of *E. globulus*, as shown in this experiment, has a significant impact on WU when compared with rainfed trees. Rates of WU in irrigated trees rose 30 to 40% within days of irrigation whereas rainfed trees show little increase in WU over the same period. This demonstrates the additional capacity of these trees to transpire when supplied with supplementary water during the 'high-energy' seasons. As the summer progressed WU of the rainfed trees increased more gradually as temperature and potential evaporation increased, then WU decreased as groundwater levels and soil moisture declined. The fact that rainfed trees reduced WU in response to limitations in water supply is of particular interest, given the proximity of the relatively shallow water table. However this may be explained by the wet conditions in winter when some of the finer roots of the trees could have died back due to waterlogging, restricting root development to the top 40 cm of the soil profile and reducing the trees ability to take up water at greater soil depths during summer. The anoxic conditions during winter could also have a toxic effect, prohibiting the growth of new roots.

Although irrigated trees would also experience these conditions, the addition of water on the ground surface increases the amount of water available to the shallow root system. This is reflected by the rapid response in WU once irrigation commenced. It is uncertain however, whether the same response would be evident in trees which have a more developed (deeper) root system that enables them to take up water from deeper, unsaturated soils or lower watertables. An increase in WU would be expected but possibly not of the same magnitude as in shallow-rooted trees. Deep-rooted rainfed trees would be able to transpire at elevated rates for a longer period over summer before water in the unsaturated soil profile becomes limiting. By late summer/ beginning of autumn, WU of the irrigated trees began to gradually decrease, most likely in response to reduction in available energy (shorter light period, lower temperatures). This is also reflected in a decrease in pan evaporation at the same time. The supply of additional water to the trees during the 'high-energy' months of the year significantly increases the magnitude and duration of elevated tree WU.

During the cooler/wetter times of the year, average tree water uptake is 40-60% lower than summer averages. It is during this time of the year that water is no longer the limiting factor in rate of WU, rather, evaporative energy is limiting. This is also reflected in low pan evaporation rates and correspondingly high WU/PE ratios of 0.9-1.4. Water demand by the trees is minimal, particularly in the low-lying , winter waterlogged conditions of the experimental site. Irrigation under these conditions would lead to surface water ponding, exacerbated waterlogging and root death.

In response to greater water availability during the drier months, the leaf area of the irrigated trees increased and was maintained at a larger area over the course of the experiment. The rainfed trees either maintained low leaf areas or decreased, despite having equivalent leaf areas to the irrigated trees at the start of the experiment. A common response of trees to water stress is to maintain lower leaf areas by limiting new leaf growth or by dropping leaves (abscission), reducing leaf area to a sustainable level. Although the irrigated and the rainfed trees differed in their leaf areas, water uptake is not proportional to total leaf area. Some trees with lower leaf area were found to be more 'efficient' transpirers, i.e the rate of WU per unit area of leaf was greater. This measurement was also shown to be quite variable between trees and within a tree over time.

Despite the fact that the effluent irrigated trees had additional nutrients supplied to them, there was no significant difference in leaf area between the effluent irrigated and the water irrigated trees. It was expected that the effluent irrigated trees would increase their leaf area in response to greater availability of nutrients, however this was not evident. Even though the nutrient concentrations in the water sampled from the observation bore in the water treatment were significantly lower than in the corresponding samples from the effluent treatment, total leaf area of the effluent-irrigated trees did not increase beyond that of the water-irrigated trees. This implies that summer water availability and not elevated nutrient availability is what influenced the growth and maintenance of greater leaf area during this experiment. Given the soil water nutrient concentrations in all three treatments, nutrients were not the limiting factor in this experiment. However, under conditions of low nutrient availability, the lack of nitrogen and phosphorus would also limit leaf area growth.

Nutrient concentrations in the soil water beneath the rainfed treatment were surprisingly higher than in the water treatment. This may be due to the leaching of nutrients from the rhizosphere of the water-irrigated trees, and infers that the 'background' soil nutrient concentrations at the site are considerably elevated. This, and the fact that leaf areas of the rainfed trees were lower than irrigated trees, supports the notion that soil nutrients were not a limiting factor in leaf area production. This would also account for the lack of difference in leaf area between the effluent-irrigated and the water-irrigated treatments. The reason for the high 'background' levels of soil water nutrients is probably due to groundwater contamination and/or overflow from the nearby effluent holding pond.

The influence of climate on the water uptake of the experimental trees is evident during and after the severe summer of 1993/94. Very little rainfall fell during this 5 month period and maximum temperatures were elevated from mid-November '93 to mid-March '94. Mean water uptake of the irrigated trees was significantly greater than the rainfed trees, one of which died at the end of summer. This demonstrates the ability of irrigation to maintain woodlots with a high leaf area index during stressful environmental conditions.

5.2 Implications for the Albany Land Disposal Site.

Comparisons between tree water uptake and pan evaporation were primarily made to extrapolate the seasonal trends in water uptake observed at Wandalup Farms to the land disposal site at Albany. Pan evaporation measurements are made by the Bureau of Meteorology at the Albany Airport, 200-300 metres from the proposed land disposal site and these data were used in the analysis. Although WU:PE ratios are often used as a simplified measure of plant transpiration or crop factor in water balance studies, there are some points which need to be considered when using this method to extrapolate trends in WU to other locations.

Firstly, the climate of the measurement site should be similar to the climate of the site to which you wish to extrapolate the WU values. If the climate at the site where WU measurements were made is significantly drier with a greater incidence of convective energy than the site to which extrapolations are made, then a significant over-estimation of annual WU could result. A good of example of this is in the preliminary report for the Albany Land Disposal Site which extrapolated WU values from Robinvale, Victoria to Albany resulting in a considerable over-estimation of tree WU (WAWA, 1991). The climates of the Swan Coastal Plain (Wandalup) and Albany however, have far greater similarity.

Secondly, the meteorological conditions during the period over which WU measurements are made should be characteristic of the study site climate if the results are to be extrapolated to another location of similar climate. The measurement period should also encompass a full seasonal cycle. If a season during which measurements were made differed significantly from the average conditions, then this may cause some errors in interpretation of extrapolated values. Extrapolation of the results from Wandalup to Albany needs to be cautious due the severe summer during which part of the Wandalup measurements were made. Extrapolated WU values from Wandalup therefore, should not be considered indicative of average conditions.

Finally, site conditions other than climate, which influence WU, are likely to differ between the measurement and extrapolated sites. Soil depth, soil water holding capacity, groundwater depth, salinity, plant density, and grazing are some of the factors which affect plant water uptake. If water availability parameters at the measurement site differ markedly from the site for which you wish to estimate WU, true WU values may vary from estimates. Soil water conditions at the low-lying areas of the Albany site would be similar to the conditions at Wandalup. During winter, some waterlogging of the root system would most likely occur due to the shallow clay/gravel layer impeding infiltration, and during summer, the resulting shallow rooted trees will be dependent on soil moisture within the upper unsaturated profile of the soil. Texture of the surface soils however is different between the sites and this may account for greater water holding capacity and corresponding higher rainfed tree WU values during late summer at Albany.

Given the above errors that are possible in extrapolating water uptake values to different sites, it should be acknowledged that estimating water uptake or developing a total water balance model for a site is only an approximation of the true scenario. Therefore the implications given in this report are only meant as guidelines until water uptake data are available from Albany.

As mentioned previously, the shallow groundwater conditions at Wandalup have led to a lower than expected water uptake of both irrigated and rainfed trees. Upon extrapolation to Albany, the results should be considered indicative of waterlogged sites in the lower part of the landscape. It is at these areas of Albany that shallow clay/rock may impede infiltration creating intermittent saturated conditions approximately 0.4 -1.5 m from the surface. This implies the water balance estimated for the Albany site may overestimate the evapotranspiration component, particularly during the wetter months. The remaining soil types at higher elevations have deeper solum profiles, reducing the incidence of waterlogging and permitting deeper root penetration. It is at these more suitable soil types that WU of either irrigated or rainfed trees is expected to be greater than what the extrapolated Wandalup figures imply. Given this, the estimated Albany WU values should be considered as representative of the lower end of the range in water uptake at the site.

Annual pan evaporation at Albany is 207 mm lower than at Wandalup and as a consequence, the estimated WU values for Albany were approximately 5.7 - 8.2% lower than WU values at Wandalup. Because of the extrapolation method used, the seasonal trends in estimated WU are the same as the measured values at Wandalup. Highest WU was estimated to occur during the late spring and early summer months, with significant reductions in rainfed tree WU during late summer. Winter WU values were estimated to be just over half that of the summer values. As discussed above, real measurements of WU at Albany are expected to differ slightly from the estimated values in both quantity and temporal pattern. Winter and spring are cooler at Albany and therefore real WU during this period is expected to be somewhat lower. Summer temperatures, on average, are also lower and may partially account for lower evaporative demand during this time of the year. This may also imply that the onset of water stress in rainfed trees is later in the summer than is the case at Wandalup. Site conditions, such as the solum depth, incidence of waterlogging and soil texture, would also have a significant impact on real WU values at Albany. As the Wandalup-derived values are really reflective of the worst WU performance (winter waterlogged conditions), estimates of the upper range of WU values at Albany are needed.

A short term study of irrigated *E. globulus* WU at Wellard on the Swan Coastal Plain (Marshall and Chester, 1991), estimated annual WU at Albany to be 842 mm (recalculated using data from Bureau of Meteorology, Albany Airport). The plantation at Wellard displayed very vigorous growth and was situated on deep sands and no waterlogging of the root systems was evident. These measurements therefore may be more indicative of trees growing on deeper soil profiles at Albany, compared with the shallow waterlogged soils that Wandalup represents. It should be noted however that the Wellard study was only of 23 days duration during Spring (September) and full annual WU estimates were calculated by correlation analysis with WU values from a nearby (Kwinana) rainfed plantation of *E. camaldulensis* measured on the same days. Monthly estimates of Albany WU were determined by multiplying WU:PE ratios by Albany Airport monthly pan evaporation. The estimated annual water uptake at Albany however is expected to be greater than 716 mm because the irrigated plantation would be less water deficient during summer than the rain fed Kwinana plantation used to derive the long-term estimate. Using the % difference in observed summer WU between the rainfed and irrigated trees at Wandalup, an approximation of 'summer-corrected' annual WU of the deep rooted trees at Wellard can be calculated and then extrapolated to Albany. This results in a 347 mm per annum increase in WU for Wellard and increases the estimate of annual WU at Albany from 842 mm to 1067 mm. Although this calculation involves many assumptions it does provide an estimate of the maximum annual tree WU that is likely for the Albany site. However, given the variability of the site conditions at Albany, average annual WU for irrigated trees at the Albany site is likely to be between 610 mm (effluent-irrigated, extrapolated from Wandalup) and 1067 mm (effluent-irrigated, extrapolated from Wellard) or about 838 mm.

Although the Albany WU estimates can be corrected for site and climatic conditions, they are still lower than the evapotranspiration rates incorporated in the water balance model for the Albany land disposal site. A preliminary study of the options for disposal of treated wastewater (WAWA, 1991) implied an annual evapotranspiration (ET) rate (not including interception) of 1881 mm and ET/PE (equivalent to WU/PE) ratio of 1.37 for irrigated E. globulus. Using information from the Wellard study (Marshall and Chester, 1991) and guidelines from the Victorian Dept. Conservation, Forest and Lands, and Victorian EPA, this excessive estimation of annual ET was revised in the subsequent planning study (WAWA, 1992) to 1249 mm. It should also be noted that this revised value represents a

Table 3: Comparison between estimated Albany irrigated tree WU from Marshall and Chester (1991), the present study and WAWA (1992).

	Estimated Albany Water Uptake from								
	Wellard[1]			Wandalup[2]			Kinhill[3]		
	WU/PE	mm Av.	mm Wet	WU/PE	mm Av.	mm Wet	WU/PE	mm Av.	mm Wet
January	0.46	96	81	0.33	69	58	0.93	196	164
February	0.36	62	58	0.36	62	58	0.93	138	148
March	0.51	76	71	0.31	46	43	0.93	133	130
April	0.74	71	58	0.49	47	38	0.93	92	73
May	1.00	68	43	0.71	48	31	0.93	62	40
June	1.12	60	49	0.91	49	40	0.93	47	41
July	1.16	65	57	0.54	30	26	0.93	50	46
August	1.16	75	70	0.64	42	38	0.93	52	56
September	0.70	57	55	0.62	50	48	0.93	70	72
October	0.52	57	55	0.44	48	46	0.93	106	98
November	0.52	69	54	0.41	54	42	0.93	121	96
December	0.48	86	70	0.36	65	53	0.93	182	135
Annual Total		842	721		610	521		1249	1098
Monthly Mean	0.73			0.51			0.93		

mm Av.: WU in mm calculated from long term average pan evaporation for each month at Albany.

mm Wet: WU in mm calculated from pan evaporation values (WAWA, 1992) for each month of a 90 percentile wet year at Albany.

[1] From Marshall and Chester (1991), average year WU recalculated using Bureau of Meteorology long term monthly average pan evaporation for Albany. Wet year WU was calculated from PE values in WAWA (1992).

[2] Average year WU calculated using Bureau of Meteorology long term monthly average pan evaporation for Albany. Wet year WU was calculated from PE values in WAWA (1992).

[3] From WAWA (1992), WU/PE recalculated to exclude interception, average and wet WU as listed in Table 7.7b and 7.12b respectively.

median year and that a 90 percentile wet year was estimated to yield an ET of 1098 mm (Table 3). As no long term meteorological data are available for Wandalup, it cannot be determined whether the years during which the measurements were taken were above or below average in rainfall, pan evaporation etc. However, data from Perth suggest below average rainfall and above average pan evaporation.

The monthly ET/PE ratios stated in the planning study included an estimate of interception which accounted for all the variability between months. Recalculation of ET/PE, excluding interception, resulted in a value of 0.93 for each month in both an average and a wet year. In comparing the ET and ET/PE values of irrigated trees from the planning study water balance model with the values from the Wellard and Wandalup studies, it becomes apparent that the model predicts a significantly higher rate of tree water use at Albany than the estimates from both field studies. This difference is mostly due to the high (0.93) and constant ET/PE ratio used to calculate monthly ET in the model. As demonstrated by the Wellard and Wandalup field studies, the ET/PE ratio, or crop factor, varies with each month. Higher values (> 1.0) occur during the winter months when PE is low, whereas low values (< 0.4) occur during the summer months when evaporative demand is greater than the physiological capacity of trees to transpire. It is suggested therefore that if the model took into consideration this variability in ET relative to PE, estimated monthly and annual ET would decrease.

6.0 References

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Appendix 1A: Leaf area measurement method

Introduction

The method used to measure the leaf area of the plantation *Eucalyptus globulus* trees at Wandalup Farm was an adaptation of that developed by Marshall (unpublished) of the CSIRO Division of Water Resources, Perth. It provides estimates non-destructively and is readily applied to many tree sizes in both forest and plantation.

The theory was validated by him through initial leaf area estimates of 32 eucalypt trees using his method before comparing results to destructive measurements of that sample. A linear regression of estimated versus measured leaf area for that sample of trees gave an $r^2 = 0.96$.

Description of method

Theory and application

As described by Marshall:

> the (tree) crown is treated as a cylinder based on crown width (w) and depth (d) with the leafy layer of known thickness extending around the side and across the top. Gaps (g) are accounted for by deriving an equivalent cylinder with continuous leafy layer ($g = (w.d$ -gaps$) / w.d$). Crown leaf area is calculated as the product of leafy layer thickness (p) of that cylinder and the frequency of leaf occurrence (c) across that volume.

The tree crown is sighted from a suitable distance where it can be seen in its entirety through a rectangular frame mounted on a sliding track or telescoping rod. The frame is strung with a square grid of wires to divide the space into cells and it is moved along the rod or track until the tree crown visually fills the frame when viewing from the sighting position. Sighting the crown through the grid provides estimates of crown width, depth and gaps:

> Crown depth and width were obtained using the principle of like triangles (with) the sighting device ... at a known distance from the base of the tree (and the grid at a known distance from the observer's eye) in two directions at right angles. The average value of each attribute was used in the equation ... The (gaps) measurement, made at the same time as crown depth and width, is the proportion of the rectangle defined by crown width and depth occupied by the leafy layer using the mesh within the sighting frame. The average value (from the two angles) was used in the equation.
>
> Leaf occurrence was measured as the number of leaf contacts made when a bank of 10 probes, 0.3m long, mounted parallel and 25mm apart was inserted into the leafy layer. The results are

> expressed as contacts per metre. When the crowns were inaccessible, the measurements were made on branches shot down from the crown and clamped in their natural position. The thickness (of the leaf layer) was measured ... using a measuring stick. At least five measurements of each attribute were made on any one tree.

Adaptation of method

Marshall's method had to be adapted to cater for the close planting at Wandalup (up to 1250 trees/hectare) which contrasted with the natural forest stands used in developing his method. For example, having to sight most trees from close distances (8 - 12 metres) to prevent being obscured by other tree crowns meant manufacture of a larger frame to maintain measurement resolution. Compared to Marshall's original small frame of some 7 x 10cms with a 1 x 1cm grid, most measurements here required a 2 x 2cm grid within a frame of 20 x 30cm. An alternative 1 x 1cm grid within a 10 x 15cm frame was also manufactured to give greater convenience when sighting smaller or more distant tree crowns.

Some of the trees measured regularly in the Wandalup water uptake study were only able to be seen, without obstruction, from around 3-5 metres distance. With tree crowns typically up to 7 metres high, such close proximity would have produced unacceptably steep viewing angles and distortion. Therefore, in these instances the crown was viewed and measured in upper and lower "halves" at a nearly horizontal angle by viewing from a ladder placed against an adjacent tree. The two sets of griding measurements from each viewing angle were then processed separately before combining to give the overall tree dimensions and gap average.

The equation developed by Marshall (equation 1) to estimate the leaf area from the measurements was also slightly modified (equation 2) for the work of this study. It was felt that this change more correctly reflected the notion of considering the surface *area* of leaves within the *volume* of the leaf layer (m^2/m^3) compared to the original equation. In any event, both equations produced results that were generally in close agreement:

$$\text{Area}_{\text{leaves}} = \{\pi.w.d.p.g^2 + \pi(0.5w - p)^2 \cdot p.g\}\, c \qquad (1)$$

or

$$\text{Area}_{\text{leaves}} = \{(\pi.0.5w^2.d) - (\pi(0.5w - p)^2.d) + (\pi(0.5w - p)^2 \cdot p)\, g\}\, c.p \qquad (2)$$

where:

w = width of crown

d = depth of crown

g = gaps - defined as percentage occupancy of crown space

p = thickness of leaf layer

c = number of leaf contacts per metre

Appendix 1B: Estimation of initial leaf areas at Wandalup Farm

Introduction

Leaf area measurement was not initially part of the of *Eucalyptus globulus* study at Wandalup Farm, first occurring after 12 months of continuous daily water uptake measurement. Values for "Day 1" leaf areas were therefore later estimated by developing a relationship between diameter over bark and leaf area from measurements on an extended sample of trees. This result was then used to estimate the leaf area of each study tree from their original diameters recorded when beginning water uptake measurement.

Methods

The extended leaf area sample of 13 trees (along with the three original study trees) was selected from within the plantation to represent the typical form and vigour of their size. The selection also took into account the full range of diameter classes present to improve the development of a relationship with leaf area. Coincidentally, the study trees fell midway in the range of diameter classes in the plantation.

The measurement method was that developed by Marshall (unpublished), adapted here to suit the close planting at Wandalup, described fully in the accompanying Appendix 1A of this report.

Results and Discussion

The results for all trees of the extended sample, including the results of the three original study trees for that date, are given in Table 1 and represented graphically in Figure 1.

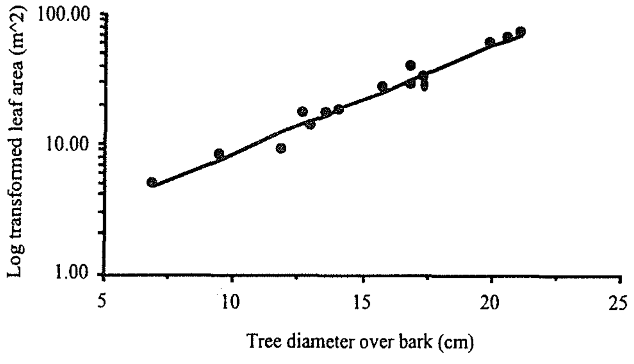

Figure 1: Results of diameter over bark versus leaf area measurement with regression line of best fit for log y transformation.

Three trees of the data set given in Table 1 were not used in the regression of diameter against leaf area. One, the Effluent-west tree, was damaged by earlier pruning of some of its branches while two of the smallest trees were considered to have unreliable results because the accuracy of the measurement technique diminishes for trees with small leaf areas.

The data set of diameter versus leaf area fitted an exponential curve best described by a log y transformation with equation of the form:

$$y = 1.248 \times 1.211^{x} \tag{1}$$

where r^2 = 0.96 and standard error of the y estimate is 0.01. It is expected that the observed exponential increase in leaf area with increasing diameter would not continue much beyond the range of diameters measured and that the trend would eventually be towards an asymptotic curve.

Table 1: Leaf area measurements of *Eucalyptus globulus* at Wandalup Farm plantation for developing relationship with tree diameter.

Tree (1)	**Diameter over bark (cm)**	**Leaf area (m^2)**
Effluent	17.4	28.34
east	16.8	39.93
west(2)	15.8	21.4
Water	17.3	32.67
east	16.9	29.37
west	12.7	17.56
Rain-fed	15.7	27.13
east	14.1	17.90
west	13.6	17.41
Large A	20.6	61.75
B	21.1	64.15
C	19.9	64.23
Small A	11.9	13.17
B	13	18.45
C(2)	6.9	17.46
D(2)	9.5	15.81
minimum	6.9	13.17
maximum	21.1	64.23
average	15.2	30.42

(1) Trees were identified by irrigation treatment received except for the extended sample of trees where naming was arbitrary .

(2) These trees were not used for developing relationship. Effluent-west was damaged and the other two considered atypical.

(3) This and the last two variables are described in the accompanying Appendix 1A of this report.

Using the resulting regression equation (1) for estimating "Day 1" leaf area it was determined that the three original study trees had leaf areas as given in Table 2.

Table 2: Estimates of initial leaf areas of the three study trees derived from equation (1)

Tree	Diameter over bark (cm)	Leaf area (m^2)
Effluent	13.8	17.52
Water	14.0	18.21
Rain-fed	13.2	15.62

Appendix 2: Foliar nutrient uptake

Introduction

Irrigating vegetation with nutrient-rich effluent can potentially recycle both waste water and nutrients, but eucalypt tree species have typically evolved on nutrient deficient soils and little is known about their capacity to use excess nutrients. Should this adaptation result in trees accessing only small amounts of excess nutrients, land disposal of effluent would result in nutrient contamination of the soil and eventually the groundwater.

Leaf samples taken from the *Eucalyptus globulus* trees at Wandalup Farm were analysed for nitrogen (N) and phosphate (P) to compare the foliar nutrient levels of the effluent irrigated trees with the levels in the control trees not receiving effluent. The following results should be seen only in the context of a restricted leaf sampling regime because the primary aim of the Wandalup study was measurement of daily water use.

Method

Leaf samples were taken three times during the water uptake monitoring; immediately before irrigation began at seven months, 18 months, and finally at study end after 21 months of irrigation. Sampling was at random from lower and mid-height positions in the crown, with juvenile and over-mature leaves avoided.

A total of around 5kg from each tree was bulked during collection and a 100g sub-sample randomly chosen for drying at 70°C for 24 hours. Samples were then ground and analysed for total N and P by the laboratories of CSIRO at Floreat, Perth W.A.

Total canopy fresh weight was measured destructively by stripping all leaves from four trees. The leaf area was measured from sub-samples of each using a leaf area planimeter so that the ratio of leaf area : fresh weight could be determined for estimating the total canopy nutrient level from the non-destructive leaf area measurements on the remaining trees.

Results and Discussion

The results of the leaf nutrient analysis for each irrigation treatment are given in Table 1.

The results of the nutrient analysis appear inconclusive with no clear trend emerging - either over time within an irrigation treatment or comparatively between each treatment. Resources were insufficient to sample the foliage thoroughly enough to provide a data set capable of rigorous statistical analysis because the main intent of the Wandalup Farms study remained water uptake measurement. The variation seen in Table 1 says more of the restricted sampling intensity than true differences in foliar nutrient levels but it does suggest that the nutrient uptake under effluent irrigation was not great enough to prove significantly different to the control trees.

Table 1: Foliar nutrient levels of N and P in *Eucalyptus globulus* at Wandalup Farm plantation following irrigation with piggery effluent, bore water and a control with no irrigation.

	Total N (μg/g)			**Total P (μg/g)**		
	Irrigation treatment			**Irrigation treatment**		
Duration of study	**Effluent**	**Bore**	**None**	**Effluent**	**Bore**	**None**
7 mths	14372	13306	12443	1799	2214	1808
18 mths	11053	10567	14230	2521	5735	4751
21 mths	9929	13881	12934	1876	1916	2295
Mean	11785	12585	13202	2065	3288	2951
Overall mean		12502			2806	

The foliar nutrient levels in the dried sub-samples were extrapolated to whole-canopy levels to give an estimate of annual nutrient uptake based on:

1) the average N (0.0125g) and P (0.0028g) level given in Table 1 (since there was no pattern in the differences in foliar uptake between the different irrigation treatments)
2) the average dry weight content of the leaf samples being 47.5% of the wet leaf mass
3) leaf area average of $2.01 m^2 kg^{-1}$ wet weight
4) the assumption that complete leaf replacement occurs annually

The values calculated thus for all trees are given in Table 2.

Table 2: Results of foliar nutrient analysis extrapolated to whole canopy levels for all trees

Tree (1)	**Diameter over bark (cm)**	**Leaf area (m^2)**	**Leaf dry weight (kg)**	**Total N (g)**	**Total P (g)**
Effluent	17.4	28.34	6.69	83.7	18.8
east	16.8	39.93	9.44	117.9	26.4
west	15.8	16.5	3.90	48.7	10.9
Water	17.3	32.67	7.72	96.5	21.6
east	16.9	35.44	8.38	104.7	23.5
west	12.7	13.38	3.16	39.5	8.9
Rain-fed	15.7	30.18	7.13	89.2	20.0
east	14.1	29.78	7.04	88.0	19.7
west	13.6	22.89	5.41	67.6	15.1
Large A	20.6	61.75	14.59	182.4	40.9
B	21.1	64.15	15.16	189.5	42.4
C	19.9	64.23	15.18	189.7	42.5

Small A	11.9	13.17	3.11	38.9	8.7
B	13.0	18.45	4.36	54.5	12.2
C	6.9	17.46	4.13	51.6	11.6
D	9.5	15.81	3.74	46.7	10.5
minimum	6.9	13.17	3.11	38.9	8.7
maximum	21.1	64.23	15.18	189.7	42.5
average	15.2	31.51	7.45	93.1	20.8

Conclusion

The foliar sampling regime was severely limited because resources available for the study were concentrated on water uptake measurement. Foliar analysis did suggest, though, that even after two years of growth under irrigation, nutrients available in the effluent were not used advantageously by the trees at a level significant enough to be easily observed.

These findings need further study to be confirmed but they have the implication that excess nutrients may not be used by eucalypt trees to any great extent and therefore effluent irrigation would result in contamination of the soil and groundwater.

Appendix 3: Water uptake measurement and single-probe technique

Introduction

Sap velocity in woody stems is readily measured with electronic data loggers that use heat applied as a tracer within the sap stream in regular, short pulses. Water uptake values are then derived from the product of the sap velocity and sapwood area (conducting wood area) of the stem for each logging period. In practice, however, erroneous results can easily be produced because sap velocity varies both radially and circumferentially in each stem, hence rigorous procedures need to be applied when installing the logging equipment.

The Custom Electronics heat pulse logger (DSIR, Soil Conservation Service, Aokautere, New Zealand) uses four separate probe sets that reduce error by sampling sap velocity at four depths into, and around, the stem to average radial and circumferential differences. The logger software then fits a curve to this unique velocity/depth measurement to calculate total sap flux for each log interval.

Application of the heat pulse loggers was advanced by the procedure established by Marshall (1989) wherein the conducting wood of a stem is accurately characterised with the heat pulse logger to determine optimum probe position instead of placing them at random. His technique, later refined to speed the process (Marshall and Chester, 1992), also created the potential for modifications to be introduced so that one heat pulse logger could be used to monitor up to four trees with negligible loss of accuracy.

Method

General

The conducting wood characterisation introduced by Marshall (1989) involved establishing the four sets of probes in a stem and advancing them to a different depth every 24 hours so that each position was sampled at three different depths. The disadvantage of this original procedure was that it required repeated site visits and did not necessarily detect all anomalies in the conducting wood because of the limited range of depths sampled.

A later refinement of the technique was to contract the sampling time to sequential manual pulses conducted as quickly as possible (maximum of 10 minutes, though typically three minutes per depth) simultaneously at four points of equal depth around the circumference. The "sap velocities" of all four probe positions (actually represented by a readout of time on the logger) is recorded for each depth before advancing the probes at 5mm increments to the full depth of the stem or the limit of their length. Probes are typically 70mm long, hence up to 14 point samples could be made for each of the four positions around a stem.

These point sample results are graphed against depth into stem so that differences in the four "sap velocities" and the plot of their average at each depth can be examined to determine an optimum depth for each probe position. The ideal is to have an average profile for any given stem that represents the smooth asymptotic curve as fitted to the data in the logger software, but frequently smaller trees exhibit a strongly asymmetric sap velocity profile that needs experienced interpretation to prevent anomalies in the software output. The eventual aim is determine from the manual readings which depths to position the probes so that they lie on the curve near the foot, the tail, and either side of maximum velocity for that stem.

Single-probe application

Single-probe sap velocity measurement was originally developed as an adaptation to suit the physical limitations of small diameter stems (1 - 10cm diameter over bark) where it was physically impossible to mount four probe sets in the stem. This was combined with modifications to the logging equipment to extend the heater and data cables to ten metres length (from the original 1.5 metres) so that four individual stems within a 20 metre plot diameter were able to be measured with one logger. Several water uptake studies since conducted on numerous shrub species confirmed the success of the single-probe technique and led to its application on trees.

The major premise of the single-probe technique, in trees or shrubs, is to be able to reliably generate the equivalent of the normal four-probe measurement from a single-probe setup. A feature of the characterisation procedure outlined above is that it provides a comprehensive sampling of sap velocity at all depths for each probe position, hence the sap velocity of any one point sample is known relative to all others. Therefore, the sap velocities of the other three points can be accurately modelled from the one point of measurement to give a four point record for each log interval.

The characterisation must be conducted over a short time and under constant environmental conditions (preferably at, or near, midday) because the relationship between each point sample can change and invalidate the subsequent modelling of the other points. Also, the assumption made in all cases when applying the heat pulse probes in this way is that flux variations resulting from diurnal changes in the depth of maximum velocity and the sap velocity profile are proportionally insignificant to the total daily flux of that stem.

The single-probe adaptation has been validated through comparative water uptake measurement using both one and four probe setup simultaneously on the same trees - following the characterisation procedure outlined above. Operationally, it has been found most convenient to establish a single probe set at the point of maximum sap velocity in a stem after initial four-position characterisation. Long-term measurement can begin quickly this way before processing the results of the characterisation and it also provides the greatest convenience for producing daily flux calculations from the sap velocity data.

Processing the data from a single point measure has so far been done by generating a simulated four point data set (based on characterisation results) in a spreadsheet program for each log interval to suit the processing requirements of the standard heat pulse software (Custom Electronics). Alternatively, the software could be rewritten in future to input the characterisation results and to directly produce daily fluxes from the sap velocities of one probe set.

Water uptake in small stems and shrubs follows principles identical to that described above for trees, except it is assumed that circumferential sap velocity differences are less significant and radial differences more significant than for trees. In practice, this means that characterisation is done at only two positions (usually opposite sides with drilling having to go right through the stem in many cases) and that the probes are advanced into the stem at 2.5mm increments to give maximum sampling from the narrower conducting wood.