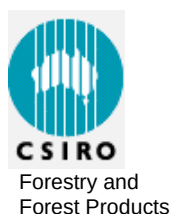




Irrigation management and groundwater uptake in young tree plantations growing over high watertables

**Final report for the RIRDC/Land & Water
Australia/FWPRDC/MDBC
Joint Venture Agroforestry Program**

by P.J. Polglase, S. Theiveyanathan, R.G. Benyon
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Foreword

Integrating trees into the agricultural landscape remains a significant challenge in Australia where objectives often are to contribute to remediation of the environment as well as to provide a commercial product. In irrigated regions, rates of growth can be increased because of the availability of water, but this needs to be managed wisely as the cost of fresh water will increase into the future while its availability is likely to decrease. For trees to have significant impact on watertables it is critical that tree species be properly matched to sites, including soil types and positions in the landscape where trees can be reasonably expected to take-up groundwater on a sustainable basis. They also need to be managed to grow well.

This report describes results from a three-year trial in young eucalypts irrigated with fresh water near Deniliquin in south-western NSW. The area is characterised by a long history of irrigated agriculture, and as a consequence the mostly saline watertables have risen often to within 3 m of the soil surface. Through a variety of avenues, tree plantations are increasingly being established in the region for on-farm diversification, to generate a commercial wood product, and for environmental benefit.

This research has shown that given appropriate site selection and management practices, tree plantations can be established to:

- Minimise both the volume of irrigation water applied and the proportion wasted to groundwater;
- Maximise groundwater uptake; and
- Grow wood at fast rates.

Outcomes would achieve the multiple objectives of establishing a plantation for environmental benefits while growing wood at commercially viable rates. Their implications also goes well beyond irrigated areas – the general principles applying equally to many dry-land situations with high non-saline watertables and where trees are considered one alternative to environmental remediation.

This project was funded by the CSIRO, Agriculture, Fisheries and Forestry-Australia, and the Natural Heritage Trust in collaboration with State Forests of NSW, and was managed through the Joint Venture Agroforestry Program (JVAP). The JVAP is supported by three R&D Corporations — Rural Industries, Land & Water Australia and Forest and Wood Products. These Corporations are funded principally by the Federal Government.

This report, a new addition to RIRDC's diverse range of over 800 research publications, forms part of our Agroforestry and Farm Forestry R&D program, which aims to integrate sustainable and productive agroforestry within Australian farming systems.

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Simon Hearn

Managing Director

Rural Industries Research and Development Corporation

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Executive Summary

A main conclusion from this study is that extensive plantings of spotted gum (*Corymbia maculata*) on prior stream beds in the Deniliquin region would:

- (i) Achieve good rates of plantation growth and production of wood for a local industry,***
- (ii) Use significant amounts of groundwater and potentially assist in controlling regional groundwater balances, and***
- (iii) Require little irrigation, thus conserving fresh water sources.***

Background

In the low rainfall regions of the southern Murray-Darling Basin (<600 mm) tree plantations may need to be irrigated to achieve commercial rates of growth for conventional forest products. Potential irrigation demand is high (> 16 ML ha⁻¹ y⁻¹ for furrow irrigation) and is greater than most landholders or managers would be willing to apply to tree crops. As the cost of fresh water for irrigation rises and supply becomes less certain, the volume of water applied to plantations will be sub-optimal for growth.

In the Deniliquin region a long history of irrigated agriculture has caused watertables to rise, often to within three metres of the soil surface. One mitigation strategy is to plant an appropriate area with trees in the expectation that they may use groundwater, and also need less irrigation than current agricultural crops.

Water applied in irrigation can be lost through direct evaporation, deep drainage (leaching from soil), and run-off. As the availability of water decreases, and its cost increases, developing irrigation practices to minimise loss of applied water is therefore a priority.

The objectives of efficient irrigation practices are to:

- Conserve fresh water;
- Reduce losses to evaporation and drainage;
- Put more reliance on use of groundwater; and
- Gain acceptable rates of tree growth.

Specific guidance would include such information as:

- How much water to apply (volume);
- When to apply it (season);
- How frequently (interval);
- Expected rates of plantation growth; and
- How much groundwater would be used by plantations and under what site (soil and species) conditions?

This report describes results from a three-year study of growth, water fluxes and salinity, in young, flood-irrigated eucalypt plantations near Deniliquin, south-western NSW.

Sites

Five field trials were established on a range of sites that varied in soil type, and depth and quality of the watertable. Studies were initially conducted at 'Norwood Park', an irrigation rates trial in *Eucalyptus grandis*. Four trials at three 'satellite sites' were added to the project in the second year (July 1998) to extend the range of site conditions studied. A summary of sites and irrigation treatments is given in the table below. The main feature is the difference in sub-soil properties, Karawatha have deep sandy loam soils, the other sites having very clayey and saline sub-soils. The watertable at all sites was about 3 m below the surface and was relatively fresh at Karawatha, but saline to highly saline at all other sites.

Site name	Species and year established	Sub-soil properties	Irrigation treatment	Years of study
Irrigation rates trials				
Norwood Park	<i>E. grandis</i> (flooded gum), November 1994	Alkaline, saline, sodic, massive clay	No irrigation - Nil (N) treatment	1997-2000
			Two irrigations per year - Operational (O) treatment, 1 ML/ha per application	1997-1999
			Irrigation every 4 weeks, about 6-7 applications per year, 1 ML/ha per application – High (H) treatment	1997-1999
			Irrigation every 2 weeks, 0.5 ML/ha per application, every furrow irrigated – (EF) treatment	1999-2000
			Irrigation every 2 weeks, 0.25 ML/ha per application, alternate furrows irrigated – (AF) treatment	1999-2000
Billinudgel	<i>E. grandis</i> , March 1996	Alkaline, saline, sodic, massive clay	One or two irrigations per year – 1 ML/ha per application	1998-2000
Baxters	<i>E. grandis</i> , March 1995	Alkaline, saline, sodic, massive clay	One or two irrigations per year – 1 ML/ha per application	1998-2000
Karawatha-G	<i>E. grandis</i> , March 1995	Deep sandy loam with neutral chemical and physical properties	One or two irrigations per year – 1 ML/ha per application	1998-2000
Karawatha-M	<i>C. maculata</i> (spotted gum), March 1995	Deep sandy loam with neutral chemical and physical properties	One or two irrigations per year – 1 ML/ha per application	1998-2000

Irrigation to sustain growth and conserve water

Results showed that the most appropriate irrigation strategy will vary according to soil conditions.

On *shallow clayey soils* or where sub-soil properties impede root penetration, frequent irrigation in small volumes would maximise growth per megalitre of water applied while minimising losses of the water applied during flood irrigation. About 50-70% was lost to direct evaporation, deep drainage and run-off, with 30-50% remaining in soil. In these soils, only a proportion of this water is available to tree roots due the relatively high tension by which it is held. Thus, irrigation every 10-14 days in relatively small volumes of about 0.5 ML ha⁻¹ is preferred. Over a growing season (November-March) this would add about 4-6 ML ha⁻¹. Irrigation systems that increase the efficiency of application could apply even less water and more frequently.

In *deep, sandy loam soils* conducive to root development, less frequent irrigation (e.g. 4 times y⁻¹) in larger volumes (e.g. 1.5 ML ha⁻¹) would be appropriate. The sandy loam texture of the soil holds water less tightly and a greater volume is stored due to the large rooting depth, making more of the water applied available to trees.

Groundwater uptake

Groundwater uptake was substantial at Karawatha (deep, sandy loams) but minimal or moderate at all other sites, and there was also an indication that *C. maculata* used more groundwater than *E. grandis*. During the 1999-2000 growing season, groundwater use at Karawatha was 793 mm under *C. maculata* and 450 mm under *E. grandis*. These volumes represent 82% of total water used by *C. maculata* and 73% of that used by *E. grandis*.

Careful selection of sites and species, followed by appropriate irrigation strategies, are required if farm forests in this region are to achieve reasonable growth and help control rising watertables. Factors to consider for site selection are:

- Proximity to prior streams or localised sandy aquifers;
- Soil physical and chemical conditions; and
- Depth to and quality of the watertable.

Based on measured use of groundwater by *C. maculata* we calculate that the total recharge from 70 000 ha of rice plantations in the region would sustain about 14 000 ha of tree plantations (as a continuous crop) while maintaining regional groundwater balance. These plantations would need to be uniformly distributed around prior streams to minimise excessive draw-down of the watertable beneath them.

In the Deniliquin region, a significant challenge remains to integrate the above information into a management strategy at a regional scale. An effective and inexpensive method is needed to locate and map suitable sites in the region where trees can be grown to lower watertables and produce wood at economically viable rates of growth. Even in the absence of a commercial wood production venture, strategic reforestation of areas of a farm could make a significant contribution to sustainable production of rice.

1. Introduction

1.1 Water

Irrigated farming, mainly of rice, other arable crops and pasture is widely practiced in the southern region of the Murray Darling Basin (MDB) and relies mostly on the water supply from the Murray River (Fig. 1.1). For the Murray Irrigation Area (MIA), the annual target allocation for irrigation is about 14.4 million ML, but because of frequent water shortages the volume allocated is usually less than this. For example, during 1999-2000, only 35% of the target allocation was supplied to irrigators in this region.

From the total area of 716 000 ha in the MIA about 10% (70 000 ha) is used for rice but requires about 54% of the total water allocation from the Murray River (Fig. 1.1). Rising watertables and associated salinity due to land clearing and subsequent excessive irrigation have provided an incentive to change farming practices and to explore alternative land uses, including use of tree plantations. The Groundwater Resource Management Survey (DLWC 1998) indicated that, in the absence of remedial action, the proportion of land with groundwater less than two metres from the surface will increase from less than 20% today to about 50% by 2020 (Fig. 1.2). Some of the land adjacent to these irrigated agriculture fields, such as prior streambeds, has the potential to produce wood at commercial rates and to control rising watertables and soil salinity.

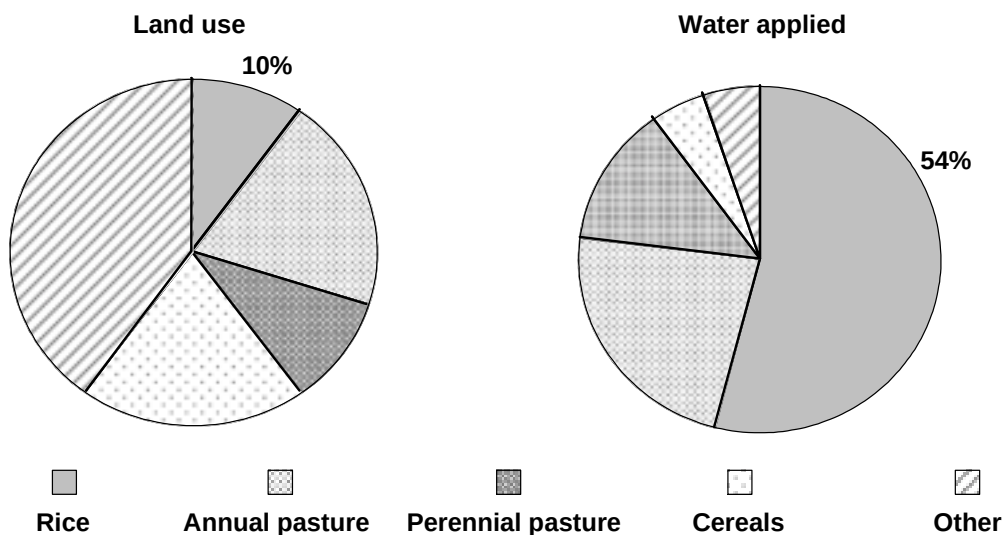


Figure 1.1. Proportion of land use and volumes of irrigation water applied for various cropping systems in the Murray Irrigation Region (MIL 1997)

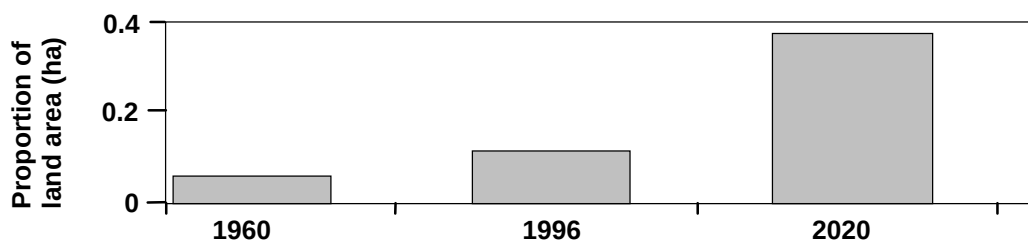


Figure 1.2. Proportion of land area affected by a watertable within 2 m of the soil surface. Data shown for the year 2020 were predicted by a groundwater flow model (DLWC 1998).

1.2 Forestry

Farm forestry is being promoted in the Deniliquin region through various extension and regional support services in government and private sectors. Most farm forests have been established on land that is not suitable for conventional agriculture (e.g. rice, wheat) either because of inappropriate soil types or because of high watertables. There is an expectation that a future market for wood products may emerge in the region, that plantations can be established and maintained cost-efficiently to optimise the return from resources invested, and that on-farm diversity will potentially lead to environmental benefit.

Plantations in the region need to be irrigated during the initial stages of growth with either fresh river water or slightly to moderately saline groundwater ($< 2 \text{ dS m}^{-1}$). If tree root systems eventually can access relatively fresh groundwater, irrigation can be reduced and perhaps permanently terminated if enough groundwater is extracted by the trees to maintain acceptable growth rates (Bari and Schofield 1992). Previous research has shown that, at some sites, the water table is lowered by plantations and as a result salts accumulate in the root zone (e.g. Heuperman 1999), possibly to the detriment of tree growth. However, the aquifer system in the Deniliquin region makes it unlikely that tree plantations can control the water table to any great extent, but they might help arrest the rise of groundwater.

Broad-scale flood irrigation has been the preferred method in the Deniliquin region for mostly historical reasons and the clayey texture of many soils. However, the water requirement of flood-irrigated plantations can be high because of inefficient application, large volumes of water being added in a single event, increasing losses to deep drainage, run off and evaporation. Calculations using WATLOAD2, an irrigation design model for tree plantations, predicts that the potential irrigation demand for flood-irrigated eucalypts is as high as $14 \text{ ML ha}^{-1} \text{ y}^{-1}$, greater than volumes that most landholders or managers would be willing to accept as economically viable (Fig. 1.3). In forthcoming years, as the cost of fresh water for irrigation rises and supply becomes less certain, the volume of water applied to plantations will be substantially less than the optimal amount required for growth unless efficient irrigation practices are employed.

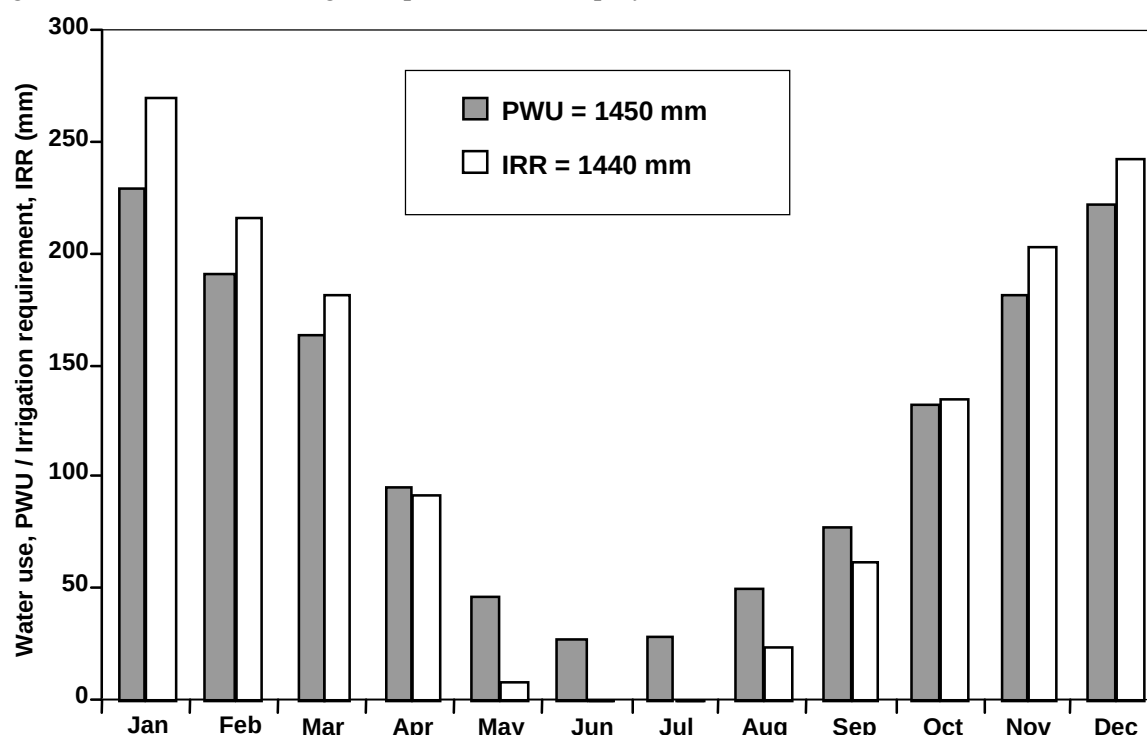


Figure 1.3. Potential water use and irrigation requirement for closed-canopy *E. grandis* growing near Deniliquin, calculated using WATLOAD2, an irrigation design model. PWU is the maximum plantation water use, IRR is the irrigation demand (Theiveyanathan *et al* 1998). Irrigation demand = (tree transpiration + interception (evaporation) + drainage loss – net rainfall) x application efficiency.

1.3 Evidence for groundwater use by tree plantations

In many parts of Australia clearing of deep-rooted, perennial vegetation from agricultural landscapes has reduced rates of canopy interception losses and evapotranspiration, and hence increased the amount of water moving through soil, causing rise of water tables and, in some cases, increased soil salinity (Robertson 1996). There is a growing expectation among farmers and the community that revegetation, particularly with deep-rooted perennials, will help repair degraded landscapes (Nambiar 2001). Large scale afforestation and reforestation projects currently are being supported through a variety of commonwealth, state, and regional initiatives.

For trees to help control high water tables in discharge locations they need to be able to access and use groundwater directly. In turn, this ability is directly related to growth and development of the root system. As trees take up groundwater, salts are largely excluded, potentially accumulating in the root zone immediately overlying the water table (capillary zone). When this happens, groundwater uptake may be reduced because roots will die back and explore less soil (Thorburn 1996). Thus, the sustainability of newly established plantations for groundwater control depends on the balance between water uptake and the accumulation and movement of salts out of the root zone. Salt movement is controlled by the rise and fall of the water table and the extent of leaching either by rain or induced by irrigation.

The most commonly used method for identifying groundwater use involves measurement of fluctuations in the water table height using piezometers installed to varying depths inside and outside the plantation. Persistent reductions in watertable depth have been interpreted as evidence for groundwater uptake by trees (Schofield and Bari 1991; Biddiscombe *et al.* 1985; Heupermann 1995; Stolte *et al.* 1996). Schofield and Bari (1991) and Bari and Schofield (1992) studied a valley reforestation strategy in the Wellington catchment, south of Perth (WA,) and found that annual minimum groundwater levels beneath an agroforestry planting (625 trees per ha) were decreased by 1.5 m over nine years relative to pasture. Heuperman (1999) showed that between 1982-1993, water tables beneath eucalypt plantations in Kyabram, Northern Victoria, were lowered by 2-4 metres. Morris and Collopy (1999) studied water use of a 10 ha plantation of *Eucalyptus* and *Casuarina* species established on a saline site under shallow (1-3 m) and saline (EC = 5-20 dS/m) water tables in northern Victoria. Modelled water balance indicated that more than half the tree water uptake was drawn from the shallow saline groundwater.

In using groundwater fluctuation as evidence for groundwater uptake, variations in recharge and interception of rain may confound interpretations. Reduction in recharge was believed to be operating at a site near Boundain, WA (Stolte *et al.* 1996) and at a site near Merredin (WA) (George and Frantom 1990), following initial drawdown of watertables and where salinities were very high (George *et al.* 1999).

Other studies have shown that amounts of evapotranspiration exceed rainfall on some sites where trees overlie shallow, saline groundwater (e.g. Greenwood *et al.* 1985; Fraser *et al.* 1996, George *et al.* 1999), and used this as evidence of groundwater use. For example, Fraser *et al.* (1996) estimated that *Casuarina glauca* trees in an agroforestry planting overlying a watertable at 1.6 m with an average salinity of 11 dS m⁻¹ obtained about 23% of their water from the watertable.

A number of other techniques, including heat pulse, stable isotope discrimination, chloride mass balance, groundwater depth and rainfall measurements have also been used to obtain more direct estimates of groundwater use (e.g. George 1991; Thorburn *et al.* 1993a; Fraser *et al.* 1995; Slavich *et al.* 1996). For example, Slavich *et al.* (1996) used stable isotopes to calculate that groundwater use by *Atriplex nummularia* (Old Man Saltbush) in southern NSW was low (average of 4 seasonal values was 15%), and that groundwater uptake occurred mainly during the dry part of the summer (51% of total transpiration).

1.4 Objectives of this study

After extensive consultation with farmers, forestry, and landcare groups in the region, it became plainly evident that guidance was needed on:

- The minimum frequency of irrigation required to sustain acceptable tree growth during the first few years of establishment;
- Whether or not plantations would eventually use shallow groundwater, and the site conditions under which groundwater use would be promoted; and
- The long-term consequences of plantation development in lowering watertables, increasing growth, whilst decreasing irrigation demand.

Thus, a cost-efficient system is required to manage irrigated plantations to ensure that good productivity is attained. Currently, there are no guidelines for conservative use of water, particularly with regard to stage of plantation development and the potential for trees to access groundwater.

The objectives of this research were to answer some of the above questions to help guide farmers to plan, design, establish and manage tree plantations under high watertables in the region. The primary aims of the study were to:

- Develop a bio-physical basis for efficient irrigation of young eucalypt plantations on sites with high watertables;
- Assist plantation growers (in the Murray-Riverina region) to adopt irrigation strategies that are effective in terms of cost, productivity, and groundwater control;
- Assess the extent to which plantations access groundwater and under what site conditions; and
- Ensure direct transfer and uptake of research outcomes through direct collaboration with the local farm forest community.

Quantifying the use of groundwater by trees is of particular interest and of generic value to low rainfall regions, whether they are irrigated or not. In the past there has been little research on the ability of plantations to access groundwater under a range of site (soil) conditions. Research undertaken at Kyabram, Victoria has provided some information with regard to interactions between soil type, groundwater, and plantation growth (Heuperman 1999). However, the remarkable variation in soil types and groundwater quality in the Deniliquin region offered an excellent opportunity to study such interactions, aided by recent advances in sap flow measurement in tree plantations (Hatton *et al.* 1995) that in conjunction with traditional water balance studies, can be used to measure the contribution of groundwater to plantation water use.

This report describes results from studies of water fluxes in young, flood-irrigated eucalypt plantations near Deniliquin, south-western NSW. Results from five field trials are used to describe the interactions among irrigation strategies, water use and water use efficiency, and to quantify groundwater use in relation to soil characteristics.

2. Research Structure and Site Description

2.1 General

The trials were located in 3- to 4-year-old plantations of *Eucalyptus grandis* and *Corymbia maculata* around the Berriquin irrigation district near Deniliquin, southern NSW (Fig 2.1, Table 2.1). The project consisted of the main trial, Norwood Park (NP) - an irrigation rates trial in *E. grandis* - and four 'satellite trials' at three other sites, Karawatha-grandis (KG), Karawatha-maculata (KM), Billinudgel (BN) and Baxters (BX) where water balances were measured with less intensity.

These sites were chosen to maintain reasonable uniformity of species, plantation age and depth to watertable, while varying the range of soil types from clay to loam textures so that irrigation management and groundwater uptake could be studied in relation to soil conditions (Table 2.2).

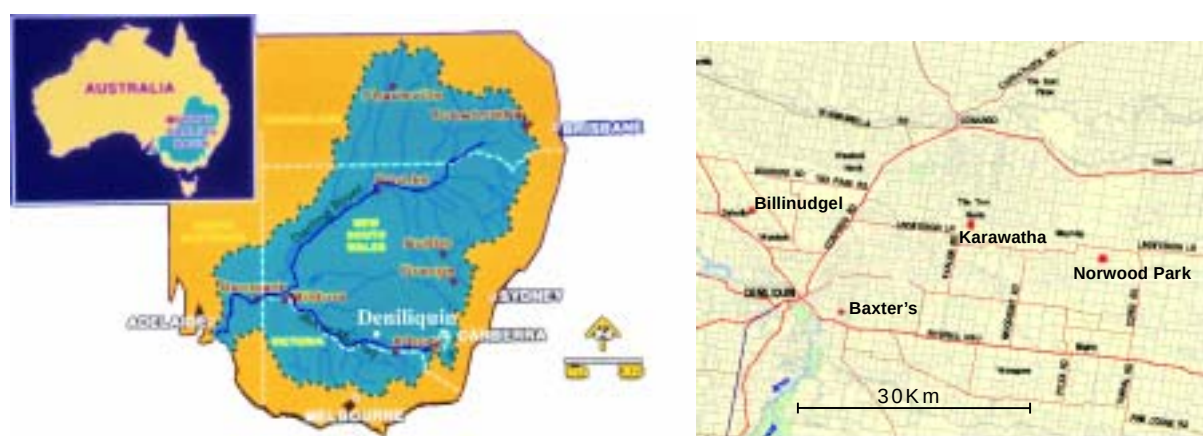


Figure 2.1 Location of Deniliquin and experimental sites.

Table 2.1 Location of experimental sites

Site	Latitude	Longitude
Norwood Park	35° 28' 09"	145° 22' 49"
Billinudgel	35° 24' 44"	144° 58' 09"
Karawatha	35° 25' 56"	145° 11' 47"
Baxter	35° 32' 57"	145° 02' 08"

Irrigation studies were initially conducted at Norwood Park, a plantation of *E. grandis* where three rates of flood irrigation were used to compare and evaluate the irrigation responses to growth, and to establish an irrigation strategy for tree plantations. The four satellite trials were added to the project in the second year (July 1998) to extend the range of site conditions studied and to compare irrigation application efficiency, and to study the contribution of groundwater to total plantation water use. A schematic diagram of the overall experimental structure is given in Figure 2.2.

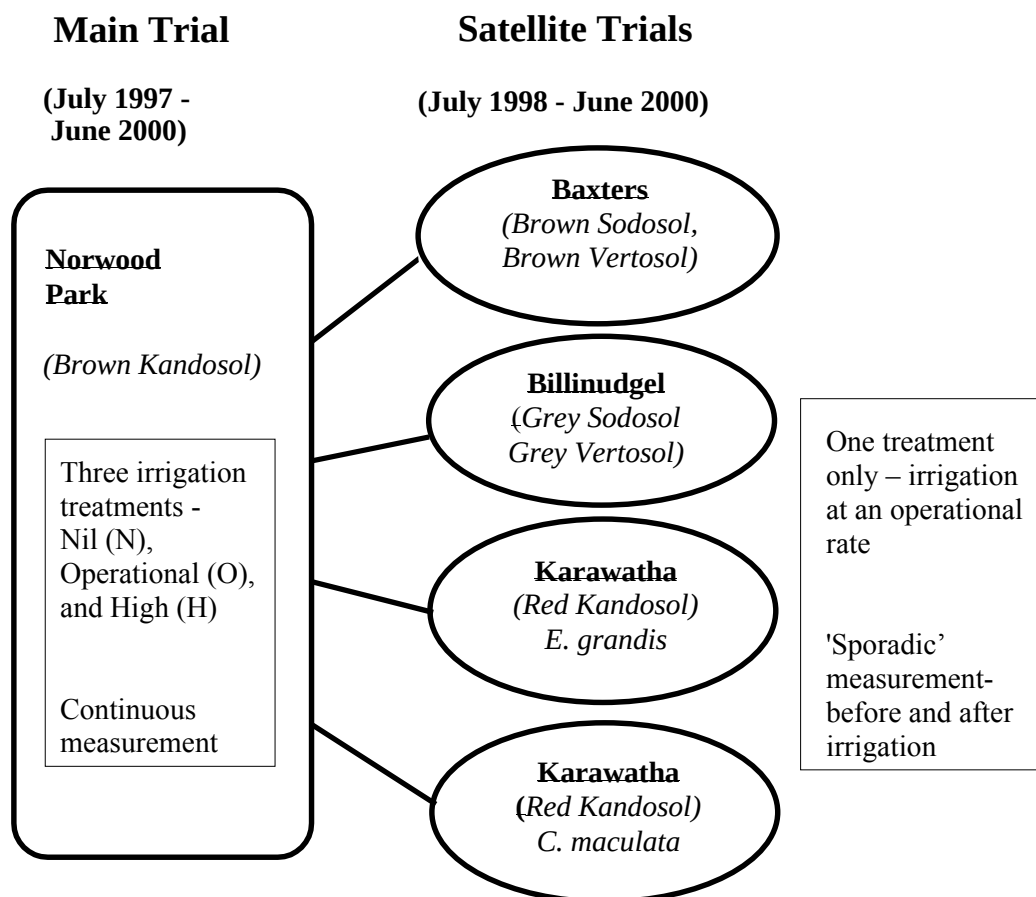


Figure 2.2 Schematic diagram of the overall experimental design. Growth, water balance and salinity were assessed in all the trials.

Table 2.2 Summary of experiments and site conditions. Karawatha-G refers to *Eucalyptus grandis* plantation trial and Karawatha-M refers to *Eucalyptus maculata* plantation trial at Karawatha. Leaf area index (LAI) is the uncalibrated value as determined from LICOR 2000 in 1998.

Trial name	Species	Date planted	Three-year MAI ¹ (m ³ ha ⁻¹)	LAI	Sub-soil properties
Norwood Park	<i>E. grandis</i>	November 1994	5.8		Alkaline, saline, sodic, massive clay
Billinudgel	<i>E. grandis</i>	March 1995	2.1		Alkaline, saline, sodic, massive clay
Baxters	<i>E. grandis</i>	March 1996	11.1		Alkaline, saline, sodic, massive clay
Karawatha-G	<i>E. grandis</i>	October 1995	18.1		Deep sandy loams with neutral chemical and physical properties
Karawatha-M	<i>C. maculata</i>	October 1995	16.0		Deep sandy loams with neutral chemical and physical properties

¹Mean annual (volume) increment

2.2. Experimental design

2.2.1 Norwood Park

The *E. grandis* plantation at Norwood Park was established in November 1994, about 40 km east of Deniliquin. In the 1997-98 and 1998-99 irrigation years, three rates of flood irrigation were applied (Fig. 2.3):

- N - no irrigation;
- - operational rate of irrigation, twice per year at the rate of about 1 ML ha⁻¹ event⁻¹; and
- H - high rate of irrigation, 6 to 8 times per year at monthly intervals during the irrigation season at the rate of about 1ML ha⁻¹ event⁻¹.

The operational rate is defined as the amount and frequency with which farmers generally irrigate tree plantations in the region in an average year. Results from this trial showed that monthly irrigation was insufficient to maximise growth, and resulted in considerable loss of water to deep drainage.

Therefore, in 1999-2000, new irrigation treatments were established at Norwood Park to see if smaller and more frequent irrigation increased growth while reducing groundwater recharge. An additional treatment was also introduced to test whether irrigating alternate furrows at a decreased rate could increase water use efficiency. The new irrigation treatments were:

- N - (no irrigation);
- EF - every furrow irrigated fortnightly at the rate of 0.5 ML ha⁻¹ event⁻¹; and,
- AF – alternate furrows irrigated fortnightly at the rate of 0.25 ML ha⁻¹ event⁻¹.

These treatments were established in plots according to a 'paired' design, the 'O' and the 'H' treatments from the previous irrigation trial each being split into an EF and AF treatment (Fig. 2.3).

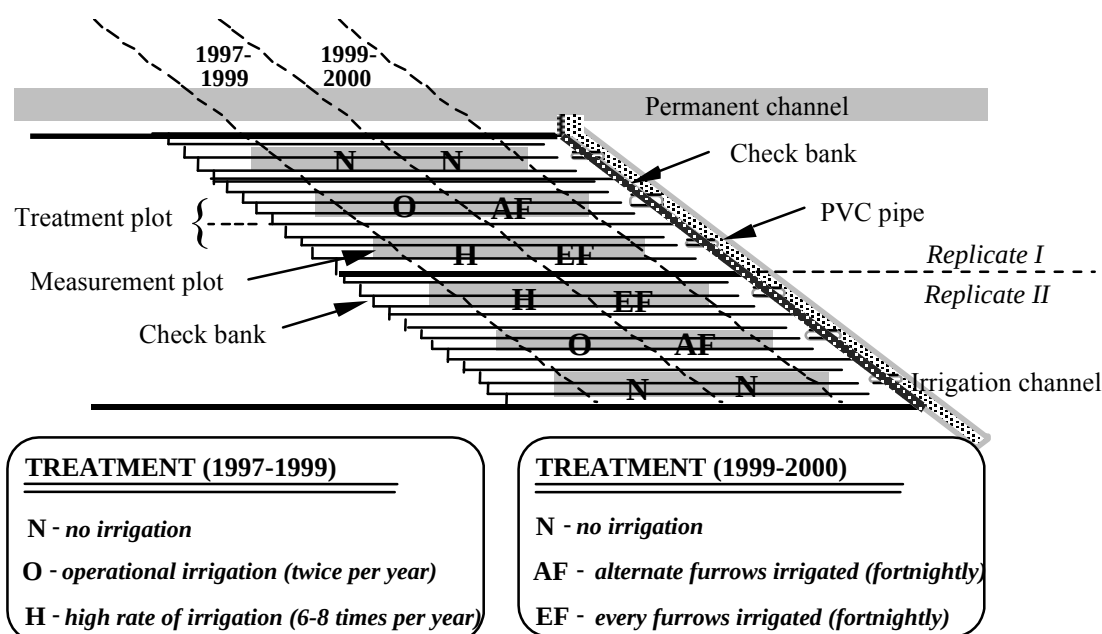


Figure 2.3 Layout of experimental treatments in the six plots at Norwood Park for the 1997–1999 and 1999/2000 irrigation seasons. The 1997-1999 treatments were replaced by 1999-2000 treatments.

About 1 ha of the Norwood Park plantation was used, the three treatments being established in each of two replicate blocks, giving six plots in total. Treatment plots consisted of four furrows and five tree-rows each 125 m in length. The furrows were flood-irrigated from one end and check-banked at the other end to prevent run-off. Measurement plots were confined to the middle row of trees (36 trees) and the two surrounding furrows.

Geometric configuration and the cross-sectional area and shape of the furrows were obtained by measuring the depths of furrows at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, and 120 cm from the mid point of the furrow to either side of the ridge. These measurements were repeated at various distances along the furrows and the overall mean cross-sectional area calculated (Fig. 2.4).

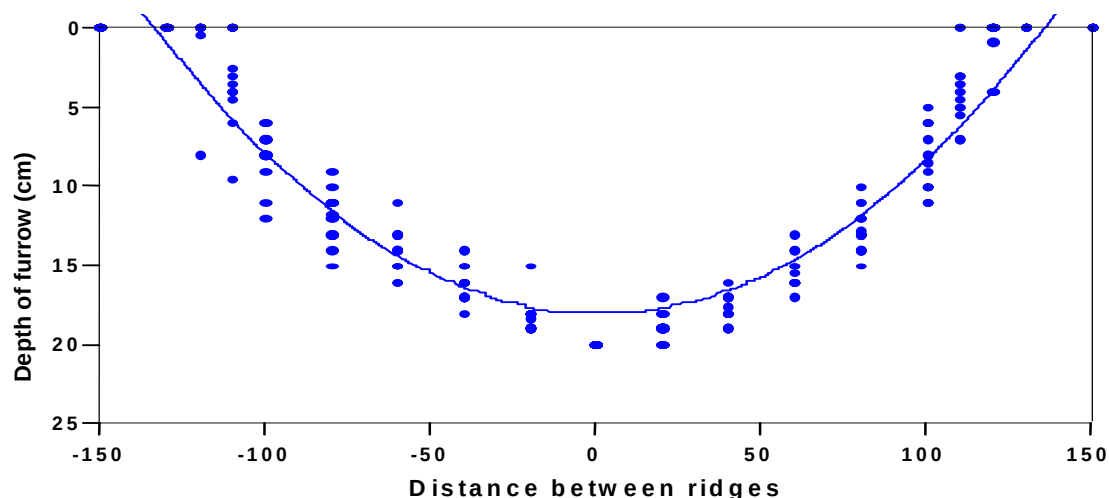


Figure 2.4 Cross-sectional representation of furrows. Depth of furrows was measured from the top of the ridge at various distances between ridges.

2.2.2 Satellite trials

Four satellite trials were added in the second year (July 1998) to extend the study to the range of soil conditions typical of the region (see Table 2.3). A single treatment of flood irrigation at the operational rate of two or three times per year was applied to each of these trials. Two replicate plots consisting of three furrows and four rows of trees, 20 m in length, were established at each trial. The furrows were flood-irrigated from one end but were open at the other end to allow runoff. Measurement plots were confined to two rows of trees and the three associated furrows.

2.3 Climate and soil characteristics

Mean annual rainfall in the region is 400 mm (Fig. 2.5), uniformly distributed over the year. Annual pan evaporation is 1900 mm, varying from a monthly low of 40 mm in June/July to a maximum of 300 mm in January. Average temperatures vary from a monthly low of 8.2°C in July to a high of 22.6°C in January. During the study period, meteorological data (rainfall, pan evaporation, wet and dry bulb temperature, solar radiation and wind speed and direction) were recorded hourly at the Norwood Park site using an automatic weather station (Starlog, UNIDATA Australia, Perth).

Soils from the four trial sites, Norwood Park, Karawatha, Baxters and Billinudgel, have contrasting physical and chemical characteristics (Fig. 2.6 and Appendix 1.4). Soils varied widely between sites (Table 2.2) but generally can be separated into soils occurring at Karawatha and those occurring at all other sites (Fig. 2.6). At Karawatha, the sub-soil had relatively low clay content, neutral pH, and was low in salinity and exchangeable sodium percentage (ESP, an index of sodicity, Appendix 1.4). Properties of sub-soils at the other sites were harsh to extreme, having high clay content (up to 50%), no structure (massive clays), highly alkaline pH, and often were highly saline with extreme ESP (up to 40%, Fig. 2.5). Soil conditions were particularly extreme at Billinudgel. It could therefore be supposed that soil conditions would be conducive for good tree growth at Karawatha, lesser so at Baxters and Norwood Park, and poor at Billinudgel.

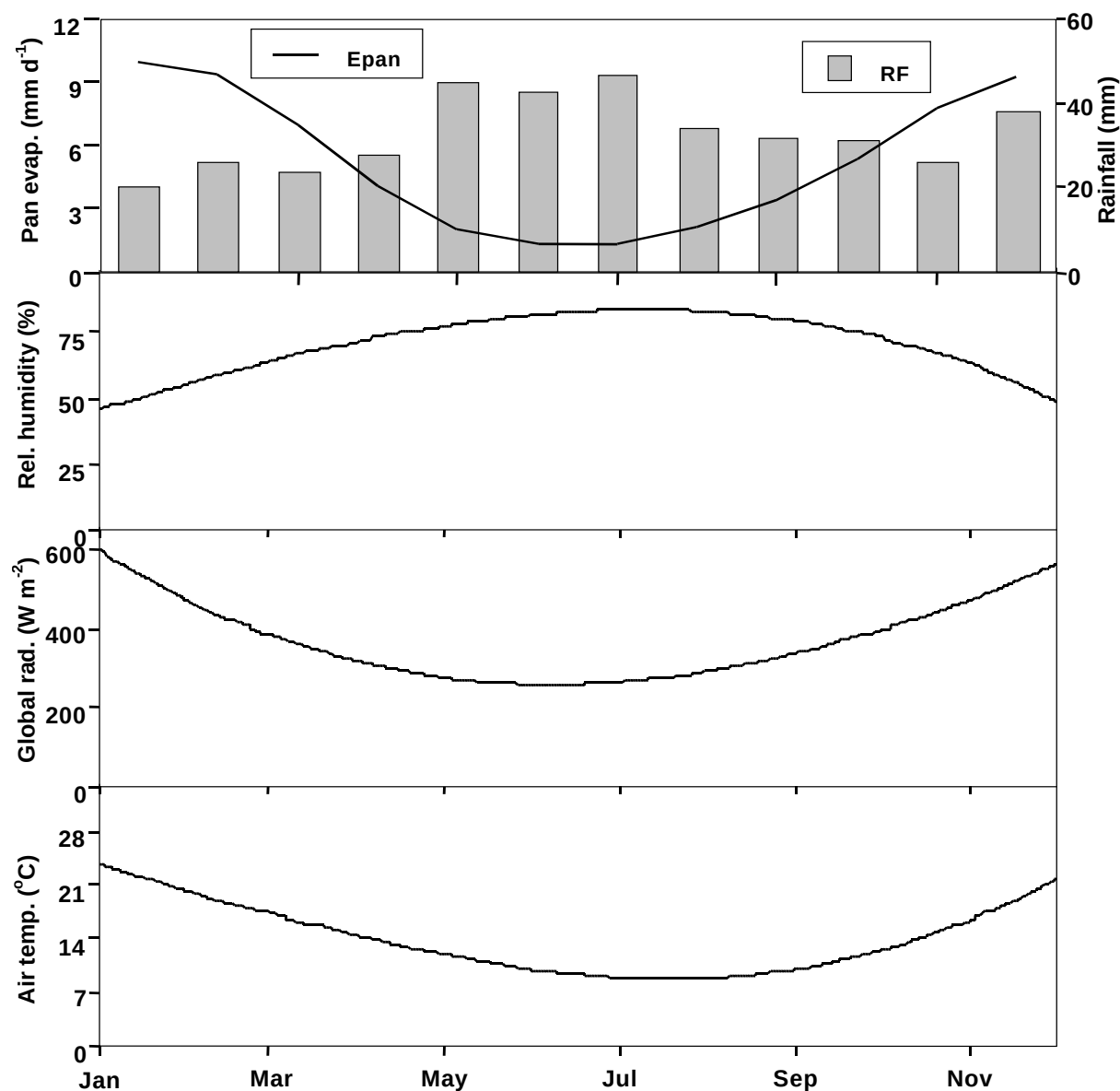


Figure 2.5 Meteorological data (15-year average) for the Denilquin region.

Soil bulk density was measured from excavated soil pits at Norwood Park and Karawatha, representing the two contrasting soil types. There was no difference between the sites, bulk density varying from 1.46 g cm⁻³ in the 0-0.05 m horizon to 1.60 g cm⁻³ at 1.50 m.

Table 2.2 Soil types at experimental sites according to the classification system of Isbell (1996). WHC is water holding capacity and Ksat is saturated hydraulic conductivity.

Site	Australian soil classification	Description of sub-soils
Norwood Park	Sodic, Mesotrophic, Brown Kandosol	Shallow heavy clay, low Ksat, high WHC
Billinudgel	Vertic, Subnatric, Grey Sodosol	Shallow heavy clay, low Ksat, high WHC
Baxters	Epihypersodic, Crusty, Brown Vertosol	Medium clay, medium Ksat, medium WHC
Karawatha	Haplic, Mesotrophic, Red Kandosol	Light sand, high Ksat, medium WHC

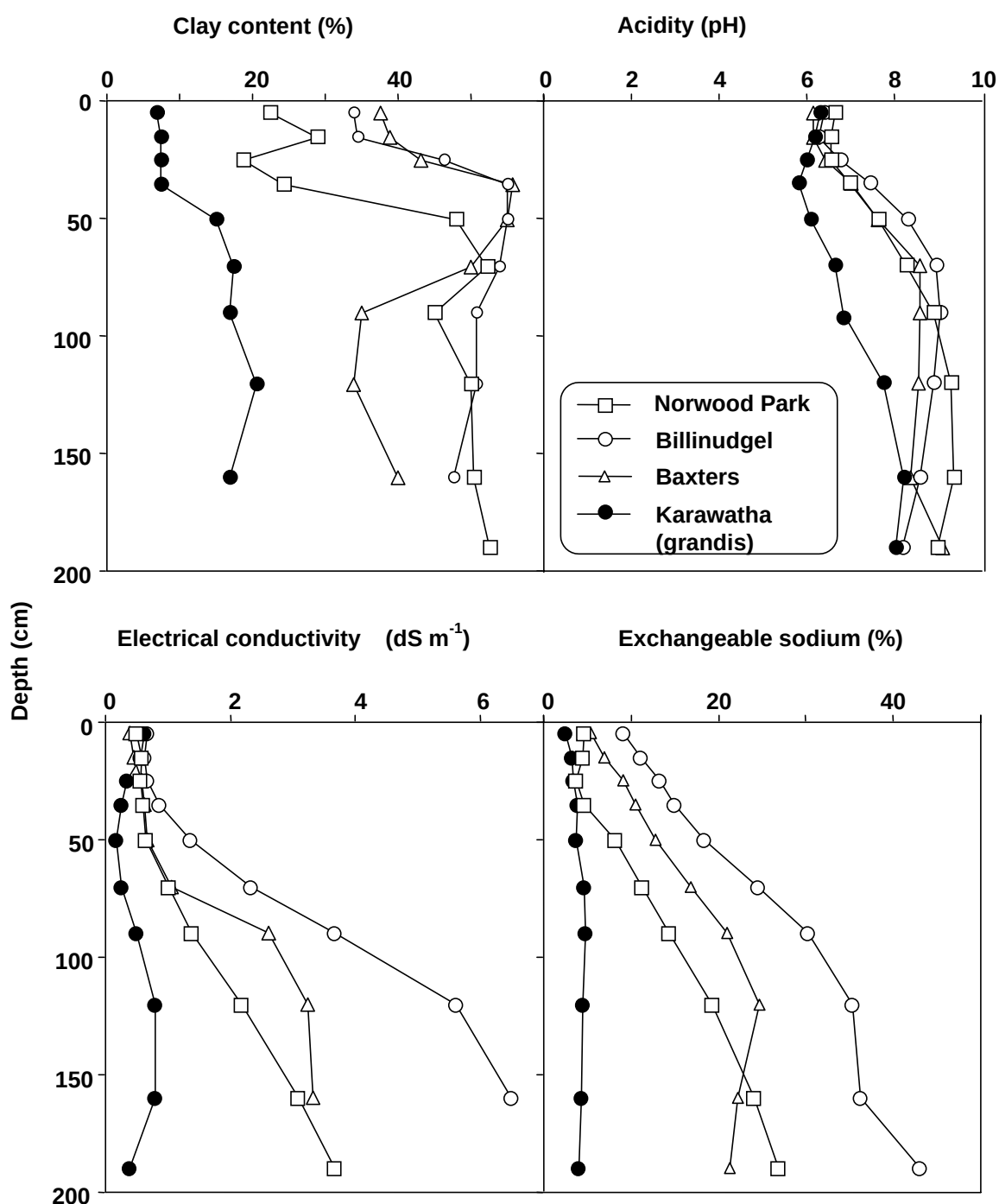


Figure 2.6 Soil properties at research sites.

2.4. Watertable depths and quality

The Murray Basin underlies most of the irrigation areas and is a geological structure characterised by a relatively thin groundwater basin which contains a sequence of sedimentary deposits of rocks of various ages (Fig. 2.7). Many of these formations are aquifers bearing water with widely varying salinity. The Shepparton formation represents the most recent and thus the shallowest river sedimentation, the sandy aquifers. These are partial semi-confined aquifers, which vary in thickness from 0.5 to 6 m and in width from a few metres to 4 km. Accession of irrigation water into this shallow aquifer system has caused a rise in groundwater levels. Because the land is flat and the aquifer relatively thin, the rise in water level has been rapid in intensively irrigated areas. The

majority of discharge from this aquifer occurs either through direct evaporation or drainage into River Murray.

All five study sites had similar groundwater levels in the shallow aquifers. During the period of study, the watertable depths varied between 2.8 and 3.2 m from the soil surface at all sites. There was a general trend for watertable depths to fluctuate by 0.5 to 1 m according to irrigation season.

The salinity of groundwater was variable within the Norwood Park site and among satellite sites, ranging from 0.2 to 22 dS m⁻¹, and was least saline at Karawatha (<2 dS m⁻¹). However, there were no seasonal changes in groundwater salinity.

Favourable soil properties for tree growth and relatively fresh groundwater at Karawatha promoted direct uptake of groundwater by trees. At other sites, conditions would seem less favourable on account of soil conditions that restricted root penetration and development, and more saline groundwater.

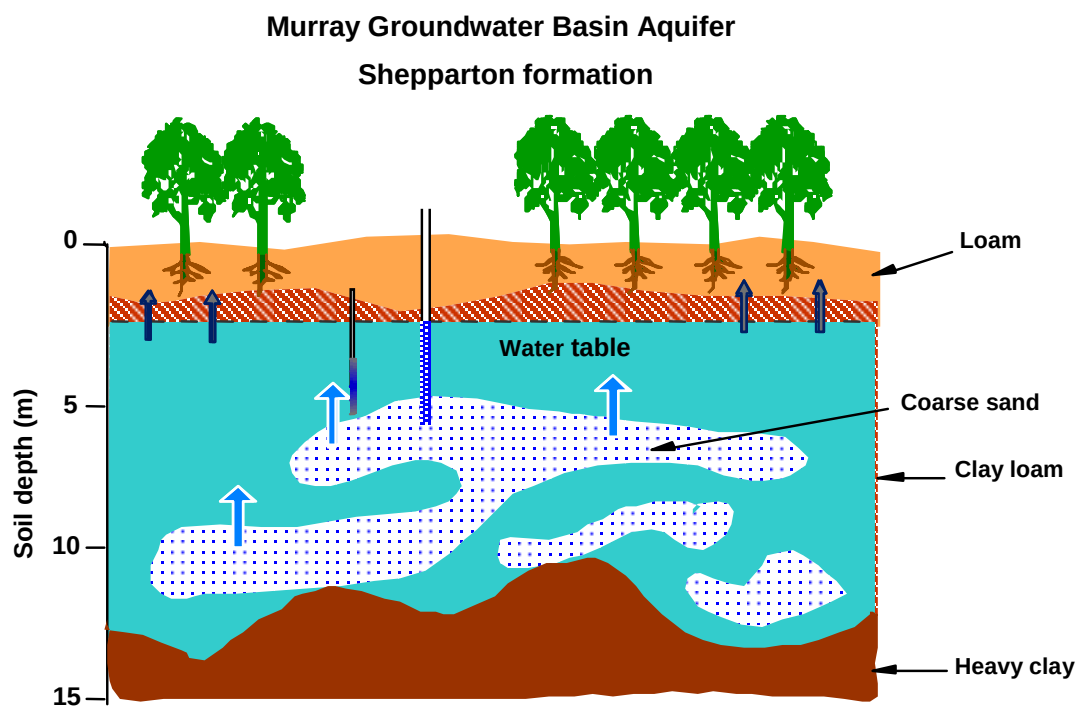


Figure 2.7 Cross-section of geological formation in the Deniliquin region. Coarse sand refers to sandy aquifers.

3. Methods

3.1 Water balance measurements

During irrigation water can be lost through various pathways, including evaporation from ponded water and subsequently from surface soil, deep drainage, run-off and in storage soil. Determining the relative importance of these pathways for loss during the first three to six days after irrigation is important to determining the efficiency of flood irrigation systems. This component of the study is defined here as **irrigation water balance**.

When water is applied through furrows it can be lost through various pathways including evaporation from ponded water and surface soil, deep drainage, or run off. The remaining water is stored in the root zone, available for uptake, or it is held in sufficient tension by soil that it is unavailable to plants. These water balance components were measured in the field to calculate plantation water use and to estimate the contribution by groundwater to transpiration. This component of the study is defined here as **soil water balance**.

The fate of water during the first three to six days after irrigation was either measured or estimated for every irrigation event at Norwood Park and at satellite sites. The irrigation water balance equation,

$$I_g = I_n + E_w + E_s + W_i + D_i \quad 1$$

was used to calculate the efficiency of application of irrigation water, where:

- I_g is total irrigation applied at the inflow point to individual plots;
- I_n is net irrigation, the volume of water retained within the root zone (assumed to be 2 m depth of soil) after irrigation;
- E_w is evaporation of water during the first few days of ponding (ponded water evaporation);
- E_s is the next few days of evaporation of water from the saturated soil surface after infiltration is complete;
- W_i is surface and sub-surface run-off (as a result of irrigation); and
- D_i is drainage below 2 m.

E_w was determined from an evaporation model (ponded water evaporation), E_s from mini-lysimeter data (soil surface evaporation) and I_n from measurement of changes in soil water content before and after irrigation (soil water retention). W_i was assumed to be 0, and D_i was calculated by difference. Details of these measurements are described in Table 3.1 and Appendix 2.2.

In addition, groundwater uptake (G , mm) was estimated fortnightly at Norwood Park and at satellite sites using the following equation:

$$G = T - ET + E \quad 2$$

where ET is the evapotranspiration estimated by soil water balance using equations (4) and (5) described later in this Section (3.4.1). Details of measurements of water balance used to estimate groundwater uptake are described in Table 3.1.

For practical reasons, measurements in satellite sites were confined to key components of the water balance, including irrigation volumes, soil water content, tree transpiration (sap flow), and groundwater depth and quality (Table 3.1). These were taken at frequencies similar to those at Norwood Park.

Table 3.1 Summary of measurements taken at the experimental sites.

Measurements	Instruments	Frequency	Norwood Park	Satellite sites
1. Irrigation volumes (Ig, mm)	Various methods	Per event		
2. Soil water content (S, mm)	Neutron moisture meter	Fortnightly		
3. Evaporation from soil (E, mm)	Mini-lysimeters	Fortnightly		
4. Tree transpiration (T, mm)	Sap flow sensors	Continuous		
5. Basal area (BA, cm)	Dendrometers	Fortnightly		
6. Tree height (H, m)	Height pole	Annual		
7. Leaf area index	Plant canopy analyser	Once only		
8. Leaf water potential (Ψ, MPa)	Pressure bomb	Once only		
9. Active root zone depth (Z, m)	Tensiometers	Periodic		
10. Groundwater depth (d, m)	Piezometers	Fortnightly		
11. Meteorological data	Met. station	Continuous		

3.2 Irrigation measurements

Four methods were used to measure the volume of water applied to each plot in irrigation and one method was used to measure total water flow into the soils. These included measurements of:

- Volumes of ponded water immediately after irrigation (Norwood Park only);
- Inlet flow velocities using dye as a tracer;
- Measurement of the velocity head upstream and downstream of the inlet channel;
- Inlet flow volumes determined from a calibrated Dethridge wheel; and
- Pressure head in two piezometers at different depths in the furrow to calculate water flow into soil using Darcy's law.

The details of these methods are given in Appendix 2.1 and 2.2.

3.3 Irrigation application efficiency

In this study, irrigation application efficiency (Ea), also known as field application efficiency, is defined as the proportion of applied irrigation water that remains in the soil for crop water use and is calculated from the following equation:

$$Ea = (I_n/I_g) \times 100\% \quad 3$$

The above definition differs slightly from others for agricultural crops where it has been defined as the ratio of crop water use to total irrigation water applied (Bos *et al.* 1993). For tree crops, unlike for agricultural crops, the depth of active root zone is great and therefore can be accurately defined. Hence net irrigation will be a reasonable estimate of crop water use. In this study, therefore, net irrigation is likely to be equal to the total water use of the plantation.

3.4 Water use

Three methods were used to determine water use of the plantations and to estimate groundwater use (Fig. 3.1).

- Total plantation water use, including transpiration from trees and weeds and evaporation from the soil surface, was estimated using a traditional soil water balance method (this accounts only for water removed from the soil, not the watertable) with the fortnightly measurements of soil moisture.

- Transpiration from the trees alone was estimated from half-hourly sap flow measurements (includes water extracted by the trees from the soil and the watertable).
- the Penman-Monteith evapotranspiration equation was used to calculate the maximum water use of these plantations under the prevailing climate in non-water-limiting conditions. Here, hourly meteorological measurements of rainfall, pan evaporation, relative humidity, wind speed, temperature and solar radiation were used to calculate the maximum water use.

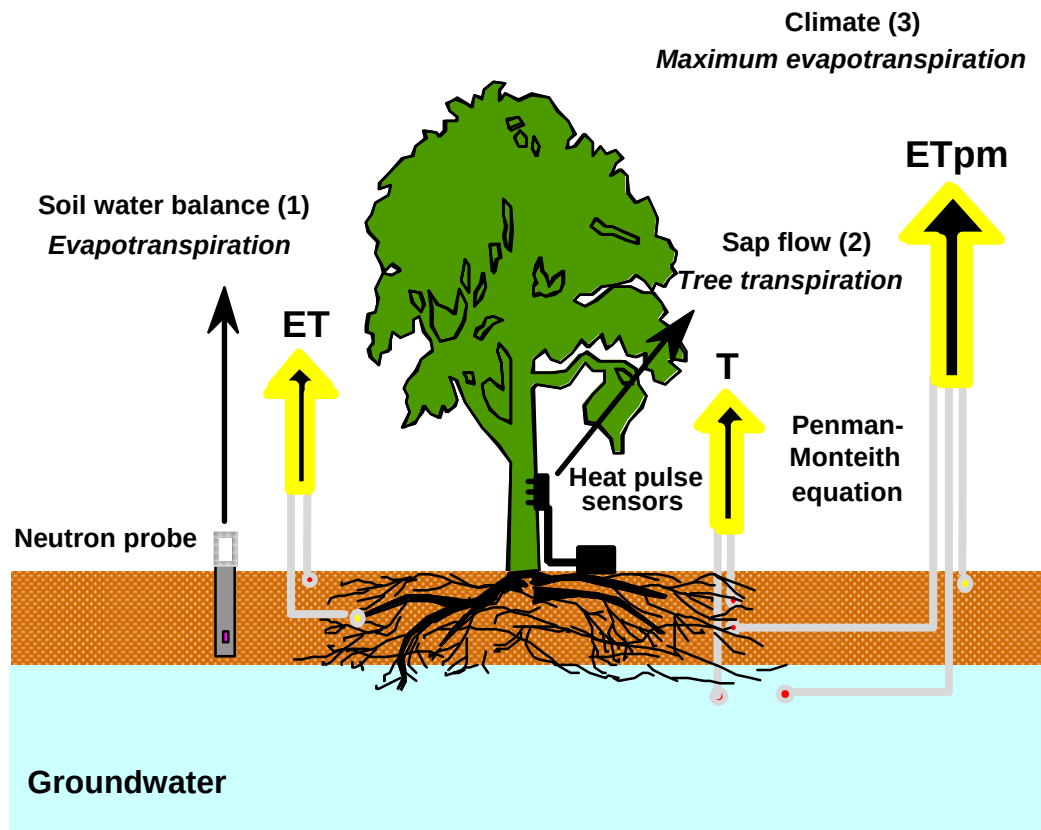


Figure 3.1 Diagrammatic representation of the three methods used in calculation of groundwater use by trees. Total plantation water use (evapotranspiration, ET) was estimated using a soil water balance method (1), tree transpiration (T) was estimated from sap flow measurements (2), and maximum evapotranspiration (ETpm) was calculated using the Penman-Monteith evapotranspiration equation (3).

3.4.1. Plantation water use

A few days after irrigation, a fortnightly soil water balance was calculated for each plot using the following equation to estimate plantation water use:

$$ET = (P_n - \Delta S) / 14 \quad 4$$

where ET is evapotranspiration estimated by water balance (mm day^{-1}), P_n is net rainfall (mm), and ΔS is change in soil water storage (mm). Net rainfall was estimated as:

$$P_n = P_g - I_r - W_r - D_r \quad 5$$

where P_g is gross rainfall, I_r is interception losses, W_r is surface and sub-surface run-off, and D_r is deep drainage below 2 m. Because annual rainfall in the Deniliquin region is low (annual total, 400 mm) and uniformly distributed, W_r and D_r were assumed to be negligible after few days of irrigation. I_r was calculated using the method described by Myers *et al.* (1996).

To measure soil water, four aluminium access tubes were installed to 3 m depth and soil water storage calculated from soil water contents measured fortnightly with a neutron probe (503 Hydroprobe, Campbell Pacific, Pachero, CA) at 0.2 m depth intervals. Neutron calibration equations were obtained at all sites from measurements of volumetric soil water content and neutron probe readings for each depth.

3.4.2. Tree water use

Sap flow sensors (SF300, Greenspan Technology, Warwick, Queensland) were used to estimate mean daily sap velocity (V_s , cm h⁻¹). Plot daily transpiration (T , mm d⁻¹) was calculated as the product of V_s and estimated plot sapwood area (A_s , m² ha⁻¹):

$$T = (V_s \times A_s \times 24) / 1000 \quad 6$$

Four trees were randomly chosen in each plot after stratifying the stand into four diameter classes to estimate mean sap velocity. Two sets of sap flow sensors were inserted into each tree and connected to a logger to record heat pulse velocities (HPV) at 30-minute intervals, that were corrected for wounding using coefficients from Swanson and Whitfield (1981). Corrected HPVs were converted to sap velocities based on wood and water volume fractions measured in each tree at the commencement of the study and using the equations of Edwards and Warwick (1984). The sapwood area of each tree was measured every 3 months using sap flow sensors to locate the inner sapwood boundary, after Hatton *et al.* (1995) and Benyon (1999). Plot sapwood area was estimated from regressions relating tree sapwood area to tree basal area.

3.4.3. Penman-Monteith evapotranspiration equation

The Penman-Monteith model (Penman 1956; Monteith 1965) had been calibrated and tested against estimates of plantation water use for an effluent-irrigated *E. grandis* plantation for three years following canopy closure (Theiveyanathan *et al.* 1998). This calibrated model was used to predict maximum water use rates at the Deniliquin sites under non-water-limited conditions from locally measured plantation leaf area index and weather conditions.

3.5 Growth and physiology

Routine measurements of growth were taken at Norwood Park and at satellite sites. Basal area was measured at fortnightly intervals using dendrometer bands. Tree heights and leaf area index were measured annually. During one irrigation cycle at Norwood Park, pre-dawn leaf water potential of trees in the three treatments was measured using a pressure chamber (Model 1000, PMS Instrument Co., Corvallis, OR) for three consecutive days starting from the day before irrigation. Three or four fully expanded leaves from the upper canopies of each treatment were sampled every day before dawn. Leaf water potentials were standardised by subtracting 0.01 MPa per metre of tree height (Myers *et al.* 1998).

3.6 Soil water potential

When there is simultaneous downward drainage and upward evapotranspiration in the soil profile, there is usually a plane in the soil where there is no movement of water, the zero flux plane. The soil layer above this plane where there is upward movement of water is the active root zone. Depth of the active root zone was determined by calculating the total hydraulic potential and the potential gradient at different depths in the soil profile.

Duplicate sets of tensiometers were installed at depths of 0.4, 0.6, 0.8, 1.0, 1.6, 2.2 and 2.4 m at two sites, one in the 'O' treatment at Norwood Park and the other in a Karawatha-*grandis* plot. Tensiometers were connected to a mercury manometer system to record variation in soil matric potential and to calculate hydraulic potential. Daily measurements of soil water tension were made for four irrigation cycles at Norwood Park and for two irrigation cycles at Karawatha.

3.7 Watertable depths

In general, groundwater flows through soil pores and cracks and between particles because of differences in fluid pressure and elevation, together known as hydraulic or piezometric head. Thus groundwater flows from areas where hydraulic pressure is higher towards lower areas. The surface of groundwater is the watertable where the pressure head is zero. Above this depth is the capillary fringe zone and below it is the saturated zone.

Hydraulic head was measured by piezometers that determine the watertable depth in soils. For each site, four piezometers, two at 3 m depth and two at 10-14 m, were installed within and just outside (<2 m) the experimental plots.

Piezometers (50 mm diameter PVC pipe) were installed inside a larger auger hole with a slotted screen of 100-200 mm length made to the end of the pipe to allow flow of water into the tube. Sand and gravel were placed around the screen and the remaining annular space between the auger hole wall and PVC casing above the screen was backfilled to the surface with bentonite clay. In order to compare the watertable levels between sites, these piezometers were surveyed to determine the elevation in relation to Australian Standard Datum.

Fluctuation of the watertable was monitored fortnightly and also logged continuously using water level recorders (DATAFLOW Systems Pty Ltd, Noosaville, Queensland).

4. Irrigation Application Efficiency

An important aspect of irrigation design is the ability to uniformly apply the required amount of water throughout the length of the field. Under flood irrigation, water infiltrates soil for a longer time near the point of entry than at the lower end, thus wetting soil non-uniformly. In order to refill the quantity of water stored in the crop's root zone throughout the length of the furrow, irrigation water must be applied in excess. With this potentially large loss, it is essential to maximise the efficiency of irrigation.

Irrigation efficiency is a key measure of the effectiveness of irrigation management and it accounts for all losses from the point of water supply to water use. Under flood irrigation in the Deniliquin region, river water is supplied through canals and channels to individual fields, and overall irrigation efficiency involves two estimates: (i) plantation water use, and (ii) volume of water delivered to the field. Plantation water use, which is the sum of tree transpiration and soil surface evaporation, determines the volume of irrigation water retained within the root zone, and can be estimated by measuring changes in soil moisture during an irrigation event.

A useful starting point for water balance studies is the volume of irrigation water applied, but statistics on this input have been lacking for plantations. Although it is difficult to obtain good historical figures for the annual volume of water applied to plantations in the region, it seems that between 250 and 600 mm has been normal for a well-established plantation. This relatively low rate in an environment of high evaporative demand (see Fig. 2.4 in Section 2) has implications for plantation productivity. Irrigation at higher rates would be needed to maximise growth for conventional forest products, unless there is clear evidence of groundwater extraction, or unless more efficient irrigation practices are employed.

4.1 Irrigation volumes

The experimental sites differed in geography, soil type, landform pattern and irrigation infrastructure. The average volume of water applied in a single irrigation varied among sites, ranging from 0.98 to 3.21 ML ha⁻¹. At Norwood Park, where water was ponded like a 'bath tub', the average application was 0.98 ML ha⁻¹; at the other sites where water was allowed to run off, the average application volumes ranged from 1.94 to 3.21 ML ha⁻¹ (Table 4.1).

At Norwood Park, the 'O' treatment was irrigated twice and the 'H' treatment about 6 to 8 times per growing season (Table 4.2). Rainfall during the active growing season (October to May) for the two years (2.5 and 3.3 ML ha⁻¹, respectively) was more than the total annual irrigation applied to the 'O' treatment (2.2 and 1.7 ML ha⁻¹, respectively). Also rainfall was distributed evenly over this period and minimised loss of water. Growth and water use in the 'N' and 'O' treatments therefore were more influenced by rainfall than by irrigation.

Table 4.1 Average irrigation application volumes for treatment plots at Norwood Park and four satellite trials during the experimental period.

Volume per irrigation (ML ha ⁻¹)						
NP 'O'	NP 'AF'	NP 'EF'	KG	KM	BN	BX
0.98	0.25	0.5	3.21	2.31	1.97	1.94

NP 'O' is Norwood Park, 2 irrigations y⁻¹ (1997-1999)

NP 'AF' is Norwood Park, alternative furrow irrigation (1999-2000)

NP 'EF' is Norwood Park, every furrow irrigated (1999-2000)

KG is Karawatha, *E. grandis*

KM is Karawatha, *C. maculata*

BN is Billinudgel

BX is Baxters

All sites are *E. grandis* unless otherwise stated.

Table 4.2 Gross irrigation volumes for: (a) the five treatments of *E. grandis* at Norwood Park during the 1997-98, 1998-99 and 1999-2000 seasons, and (b) the four satellite trials during the 1998-99 and 1999-2000 seasons. Annual rainfall is also given. The values within brackets are the total number of irrigations for each treatment during these seasons. Key to abbreviations as in Table 4.1.

(a) Norwood Park

Season	Irrigation volumes (ML ha ⁻¹)					Rain (ML ha ⁻¹)
	N	O	H	AF	EF	
1997-98	0.80 (1)	2.25 (2)	6.76 (6)			3.20
1998-99	-	1.68 (2)	8.22 (8)			4.67
1999-2000				3.0 (12)	5.8 (12)	3.99

(b) Satellite trials

Season	Irrigation volumes (ML ha ⁻¹)			
	KG	KM	BN	BX
1998-99	9.65 (3)	6.94 (3)	5.92 (3)	3.88 (2)
1999-2000	3.56 (1)	3.71 (1)	2.14 (1)	4.99 (2)

About twice as much irrigation as rainfall was applied to the ‘H’ treatment (6.8 and 8.2 ML ha⁻¹ irrigation in the two study years) and hence the growth response to irrigation was pronounced. Satellite sites were irrigated with higher volumes of water, ranging from 3.88 to 9.65 ML ha⁻¹ y⁻¹, applied two to three times during 1998-99 growing season.

At Norwood Park, during 1999-2000, when the irrigation design was modified to irrigate alternate furrows (AF) and every furrow (EF) at fortnightly intervals, the plots received 3.0 and 5.8 ML at reduced application rates of 0.25 and 0.5 ML per irrigation respectively (Table 5.1 and 5.2).

4.2 Irrigation losses

Irrigation application efficiency (E_a) was calculated as per equation (3) where net irrigation (I_n) was calculated by measuring soil moisture contents to 2 m depth before and after irrigation and adding an estimate of transpiration for those days in between the two measurements.

There was substantial evaporation during the first three days after saturation of the soil profile (Fig. 4.1). Cumulative evaporation from soil surface for these three days was described from the following equation:

$$Er = 0.665 / (1 + 851 \times \exp[-11.1 \times Sr]) \quad 7$$

where Er = relative evaporation which is a ratio of daily evaporation and pan evaporation, and Sr = relative soil moisture which is the ratio of soil moisture and drained upper limit of the surface soil (0-20 cm).

The fate of irrigation water for the Norwood Park ‘O’ and ‘H’ treatments and for the satellite trials is given in Figure 4.2. Values are for the 6 days after irrigation, and have been determined from an evaporation model (ponded water evaporation), mini-lysimeter data (soil surface evaporation) and measurement of changes in soil water content after irrigation (soil water retention). Drainage was calculated by difference.

In the ‘H’ treatment, for every 1 ML ha⁻¹ of water applied (a typical irrigation, Fig. 4.2), 25% was evaporated (15% from ponded water and 10% by subsequent evaporation from soil). Another 25% was lost after each irrigation through deep drainage (greater than 3 m depth), with the remaining 50% being retained in the soil or transpired. The end of each irrigation furrow was blocked to prevent surface run-off. In contrast, the only difference in the ‘O’ treatment was the reduced drainage (15%) because prior to irrigation, the soil profile was drier than in the ‘H’ treatment and thus stored more

water. The 'AF' and 'EF' treatments had similar losses but the overall magnitude was intermediate to that of the 'O' and 'H' treatments.

In the satellite trials where there was substantial run-off from the lower end of furrows, drainage below 3 m (D_i) was estimated using Darcy's law as described in Appendix 2.1. Run-off was calculated by difference.

In these sites, surface run-off varied from 20% to 45% due to differences in the configuration of irrigation system design (Fig. 4.3). Total loss of water in the satellite trials after irrigation varied from 55% to 75% of that applied, an inefficient strategy, and one that leaves much scope for improvement.

4.3 Implications for irrigation scheduling

The appropriate irrigation schedule (frequency and amount of irrigation) is determined by efficiency of application, depth of the active root zone, capacity of soil to hold water, and by the soil water content at which plant water stress begins. Water stress reaches a critical limit (<-2.5 MPa at Norwood Park) at the soil water content of permanent wilting point. A shallow root system thus requires frequent irrigation in small volumes because the volume of water available for trees is lower. A deep root system permits irrigation with larger volumes and at longer intervals, reducing drainage and evaporative losses.

Despite monthly irrigation in the 'H' treatment at Norwood Park and soil moisture content at depths below 1.2 m remaining high, trees were always water stressed prior to irrigation (Fig. 4.4) as determined from measurements of pre-dawn water potential. Once irrigated, however, the trees in the 'O' and 'H' treatments recovered to a higher p (-0.5 MPa on the first day and -0.3 MPa on the second day after irrigation), while the trees from the non-irrigated 'N' treatment remained stressed during these two days (p -1.5 and -1.6 MPa).

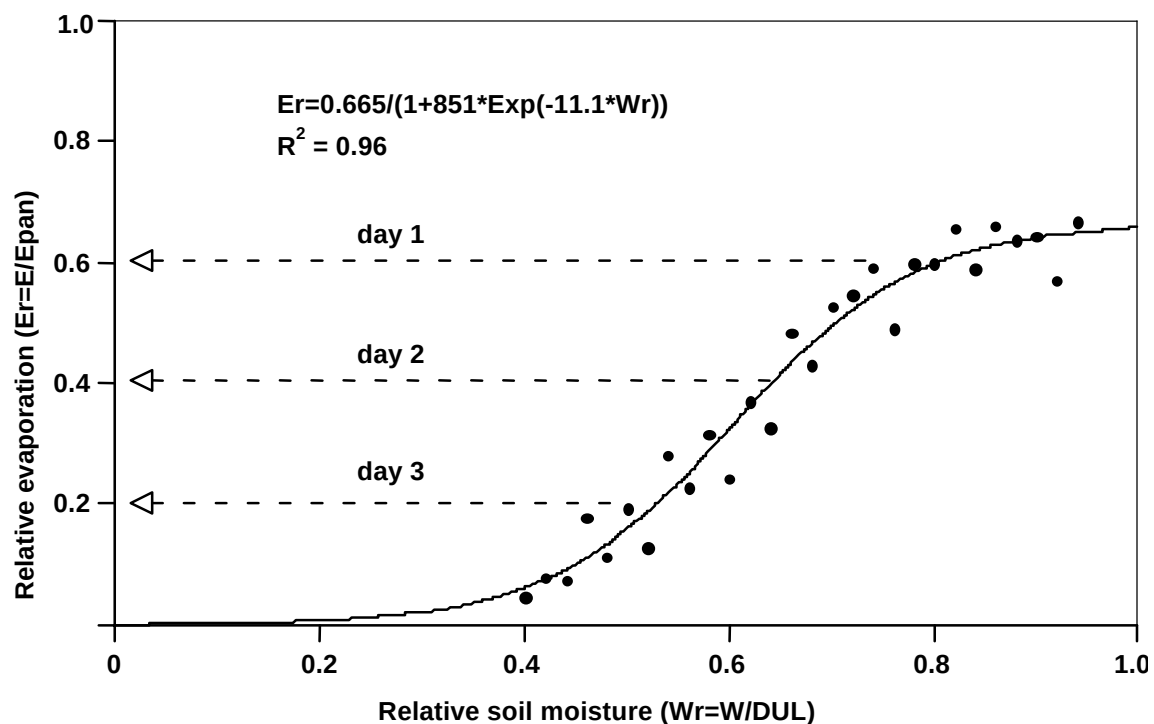
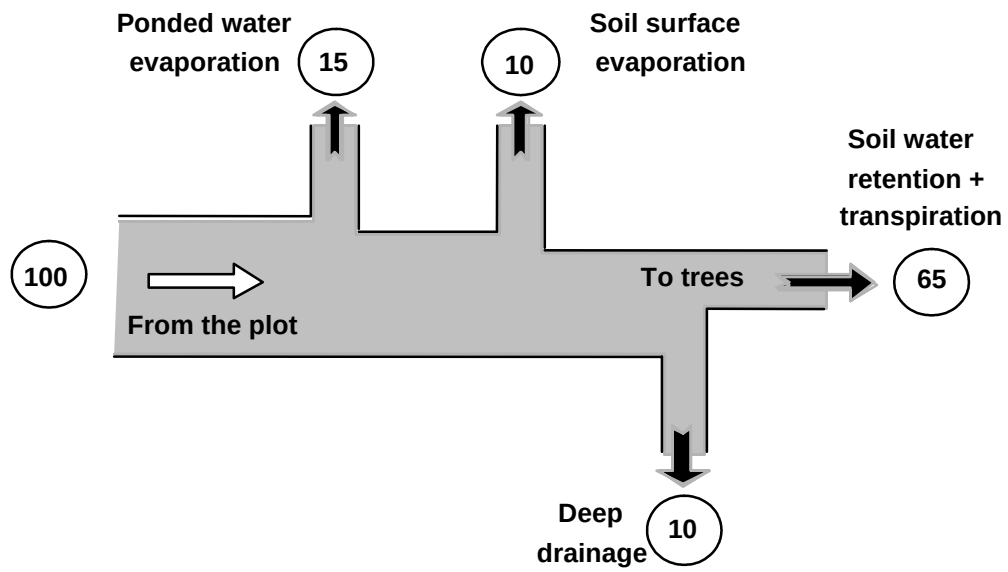


Figure 4.1 Relationship between relative evaporation ($Er=E/E_{pan}$) and relative soil moisture ($Wr=W/DUL$) of the surface soil (0-20 cm depth) during the first three days of irrigation after water has completely infiltrated. Er was calculated as a ratio of daily evaporation and pan evaporation, and Wr as a ratio of average soil moisture and drained upper limit of the surface soil.

'O' rate of application



'H' rate of application

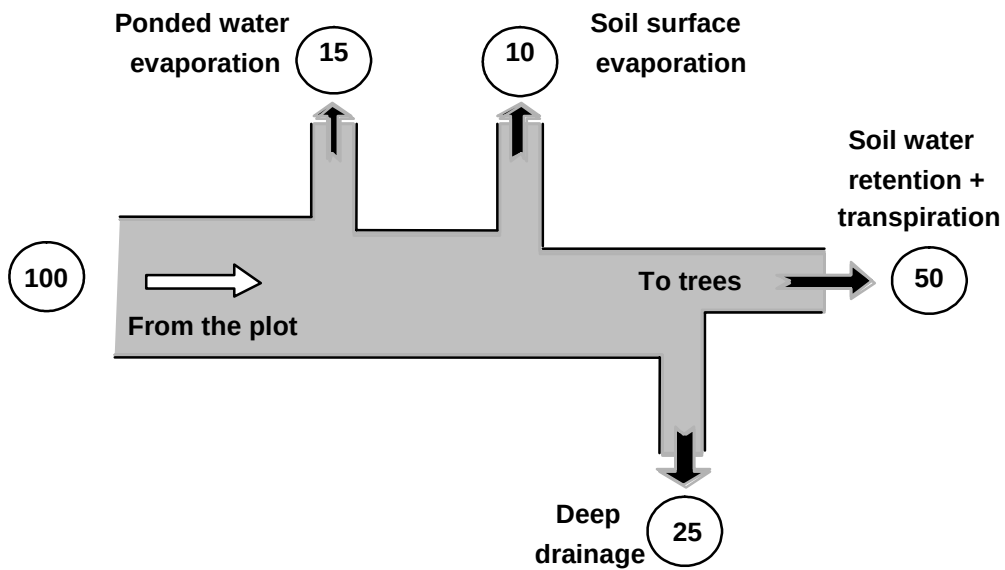


Figure 4.2 Mean fate of irrigation water in the O and H treatments at the Norwood Park irrigation rates trial. Values are percentages, but note that an average irrigation also supplied about 1 ML ha⁻¹ of water.

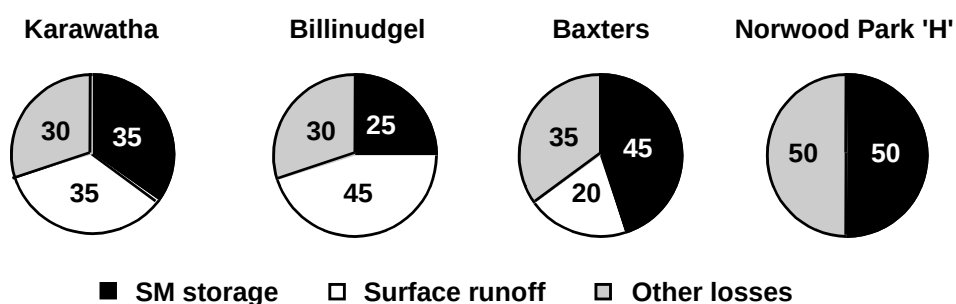


Figure 4.3 Irrigation application efficiencies for the four research sites in Deniliquin. Differences are mainly due to the varying design of flood irrigation systems.

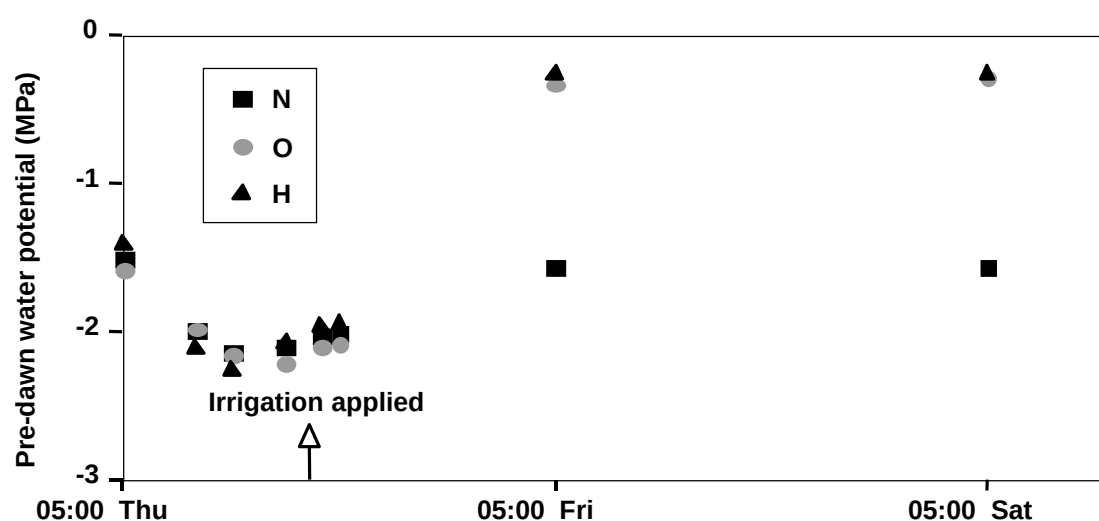


Figure 4.4 Changes in leaf water potential for three treatments at Norwood Park during the first three days of an irrigation cycle. Irrigation was applied to the 'O' and 'H' treatments on the first day of measurement, the 'N' treatment plot was not irrigated.

4.4. Water use

Plantation water use for 'N' and 'O' treatment plots was similar (Fig. 4.5). When the frequency of irrigation was increased from 2 to 6 times per year, water use in the 'H' treatment at Norwood Park was substantially increased (537 and 742 mm, respectively during the two growing seasons). However, these estimates were still much lower than estimated maximum evapotranspiration (ET_m) showing that irrigation needed to be more frequent than 6 times per year in the shallow clayey soils. Calculations of relative water use in the 'AF' and 'EF' treatments also indicated the need for more frequent irrigation. Although these massive, clayey soils hold large amounts of water, only a small proportion of it is available for use by trees, being adequate for 10-14 days or less.

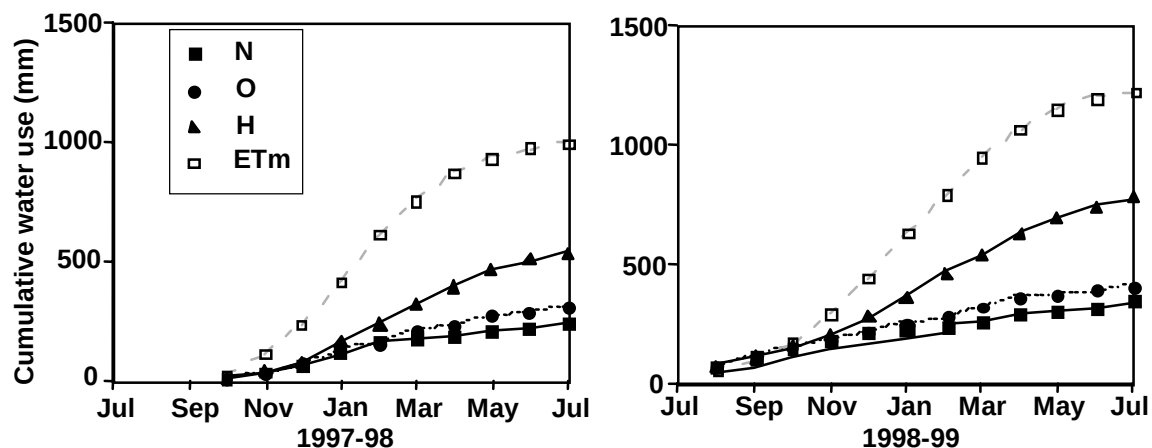


Figure 4.5 Cumulative plantation water use of the three treatments at Norwood Park for 1997-98 and 1998-99 seasons, determined by water balance. Measurements commenced in September 1997. Maximum evapotranspiration (ETm) was calculated using the Penman-Monteith equation.

4.5 Relative water use (ET/ETm)

Irrigation should aim to achieve a high ratio of relative water use calculated as the proportion of water use relative to its potential maximum (ET/ETm), and this depends upon the maximum amount of plant available water in soil. A high ratio of relative water use indicates water use is near the potential maximum, and the plantation is not stressed. As soil water depletes below a threshold level, trees become stressed and the plantation water use decreases in comparison to the maximum potential under non-water limited conditions. The soil water content at this threshold level is known as the optimum refill point. If the frequency of irrigation maintains soil water at the optimum refill point, tree water stress will be minimised.

Figure 4.6 shows the effect of irrigation on relative water use of the five treatments during the two growing seasons. The fitted line shows that in Norwood Park 'H' and 'EF' treatments, irrigation was sub-optimal for growth most of the time, overall relative water use being less than 0.6.

The amount (volume) of irrigation to apply is determined by the water holding capacity of the soil and the proportion that is available to the plant. At Norwood Park, the upper and lower limits of plant available water were determined by comparing fortnightly relative water use (ET/ETm) with fortnightly mean soil water content (Fig. 4.7). Relative water use would be close to zero for a soil water storage of 425 mm and thus the maximum plant available water (PAW) at this site is only about 75 mm (500-425 mm). Thus despite having a high capacity to store water, these clayey soils release only a small proportion to plants, the rest being held within clay by tension forces. Karawatha, with a much deeper active root system and deep sandy loam soil, has a much greater maximum PAW, close to 250 mm if we assume PAW is proportional to the depth of the root zone.

Irrigation scheduling is the process of deciding when and how much to irrigate crops. To maximise irrigation application efficiency, irrigation schedules need to be designed based on soil types. For example, applying large volumes in a single irrigation to shallow clay soils wastes much water because: (i) roots cannot penetrate below about 1 m and extract water, and (ii) PAW is in any case low in shallow clay soils compared to deep sandy loams. A substantial proportion of water will therefore drain below the root zone. The key factor that determines the irrigation schedule is the depth of active root zone. If a landowner commits a total of 4 ML ha⁻¹ y⁻¹ to irrigation, for example, it would be best to apply this in five small applications spread throughout the growing season, rather than in two large applications in the beginning and middle of the season. However, on the deep sandy loams with deeper roots systems and more PAW, irrigation at a lower frequency, but in larger amounts may reduce both the proportion of irrigation water lost via evaporation, and the amount of work involved in applying the water.

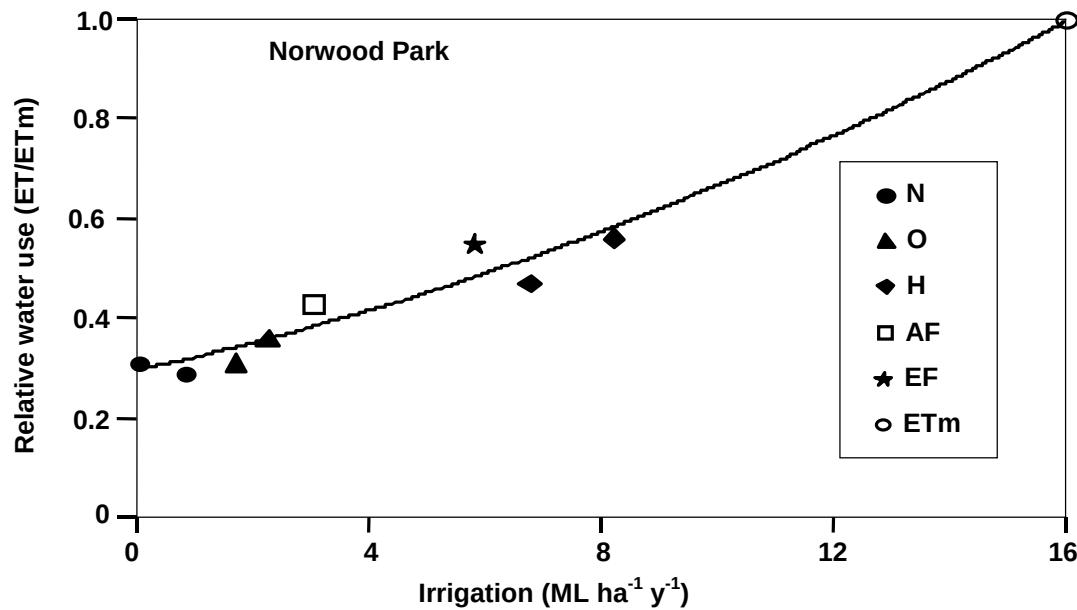


Figure 4.6 Relationship between relative water use (ET/ETm) and applied irrigation volumes for the five ('N', 'O', 'H', AF and EF) treatments and for the three growing seasons (1997-98, 1998-99 and 1999-2000) at Norwood Park. The ETm point was obtained from an irrigation design model, WATLOAD2, to estimate the total irrigation volume required (16 ML ha⁻¹) to achieve relative water use of 1.

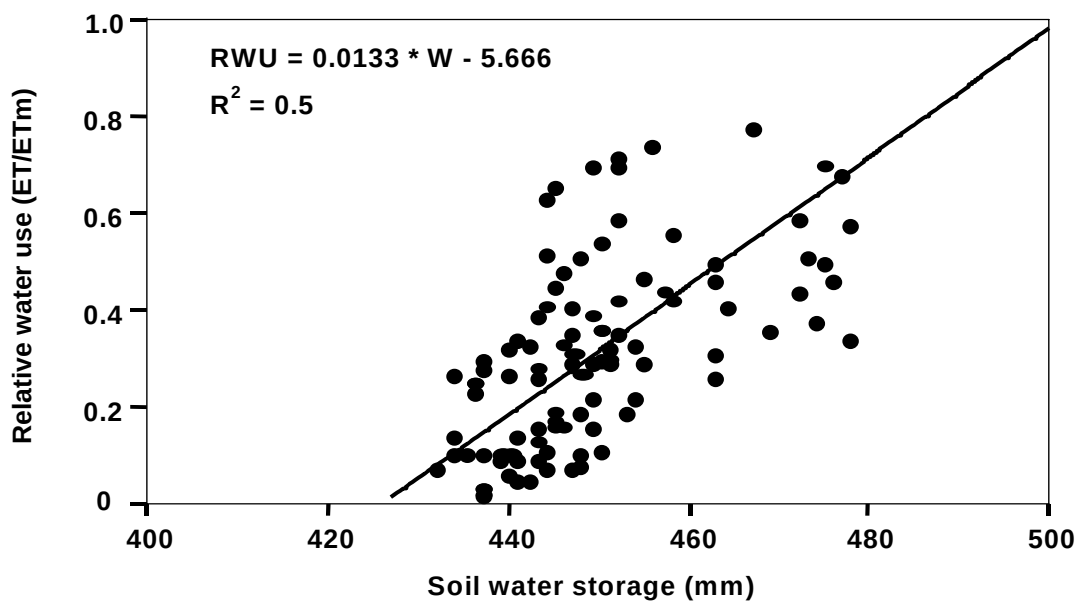


Figure 4.7 Relationship between soil water storage in the top 2 m of soil and relative water use at Norwood Park. A linear regression line fitted through the data shows that maximum water use would occur when the soil water storage reaches 500 mm. ET was estimated fortnightly from water balance measurements.

5. Growth

Growth was measured at the Norwood Park rates trial between October 1997 and October 1999, and at the satellite trials between October 1998 and October 2000. Dendrometer bands were used to measure diameter increment of individual trees initially every month at Norwood Park, and from November 1998 on a fortnightly basis. Tree heights were measured annually in winter in all plots to calculate volume increment.

5.1 Norwood Park

Table 5.1 shows annual volume growth for the three treatments over the three-year period. Growth rates were moderate and related to level of irrigation, the H treatment adding 33.5 m³ ha⁻¹ (sum of 4-y and 5-y annual volume increments) in the two years of the experiment, for a final (5-y) mean annual volume increment of 10.4 m³ ha⁻¹.

Growth in the N1 and N2 treatments is shown separately because some large trees in the N2 plot clearly were accessing water from the adjacent irrigation channel or had access to groundwater. Growth in the N1 treatment was poor, adding 7.6 m³ ha⁻¹ in the 2-y period, with growth in the O treatment being intermediate between that in the N and H treatments (Table 5.1).

Table 5.1 Summary of volume growth among treatments in the Norwood Park irrigation rates trial. Irrigation commenced in spring 1997, the 3-y volume growth representing starting conditions. The N1 and N2 replicate plots of the Nil treatment are shown separately because some trees in the N2 treatment were accessing supplementary water.

Treatment	Volume (m ³ ha ⁻¹)					
	At 3 y	4-y CAI ¹	5-y CAI	3-y MAI	4-y MAI	5-y MAI
N1	14.1	6.9	0.7	4.7	5.2	4.3
N2	17.4	17.9	9.0	5.8	8.8	8.8
O	17.4	11.2	4.9	5.8	7.2	6.7
H	18.3	18.5	15.0	6.1	9.2	10.4

¹Current annual (volume) increment

Relationships between growth (cumulative diameter increment from dendrometer bands) and water fluxes for the 2-y period are shown in Figure 5.1. Growth was linearly related to the volume of irrigation applied in all plots within the exception of plot N2 (see previous paragraph). Annual irrigation of 7 ML ha⁻¹ or more will therefore continue to increase growth, although there will be a maximum beyond which growth does not increase in response to additional irrigation.

The linear regression has the equation:

$$G = (4.3 \times I) + 17.6 \quad 8$$

where G is cumulative diameter increment (mm tree⁻¹), and I is mean annual irrigation (ML ha⁻¹).

An index of irrigation use efficiency is given by the ratio of growth:irrigation (G/I). Thus, dividing all elements in equation (1) by I gives the hyperbolic equation:

$$G/I = 4.3 + 17.6/I \quad 9$$

The form of this relationship is shown in Figure 5.2. Irrigation use efficiency is increased most at the low end of irrigation when large relative increases in growth are obtained for small increments in irrigation. Although the curve quickly flattens after irrigation of about 2 ML ha⁻¹ efficiency does continue to decline. Thus, for the flood irrigation strategy employed in this study, irrigating with increasing amounts of water leads to a proportional increase in growth with increasing loss of efficiency. Increased gains in growth must be balanced against the increased losses of water through

deep drainage and run-off when water is added frequently under broad-scale flood irrigation (see Section 4).

The linear regression of Figure 5.1a has a positive intercept on the Y-axis, indicating that growth continues in the absence of irrigation, relying on either inputs in rainfall, or access to stored soil water, or groundwater. When rainfall is included as an input (Fig. 5.2b) the regression line passes through the origin indicating that trees in these plots (N2 excluded) relied solely on above-ground inputs for their growth.

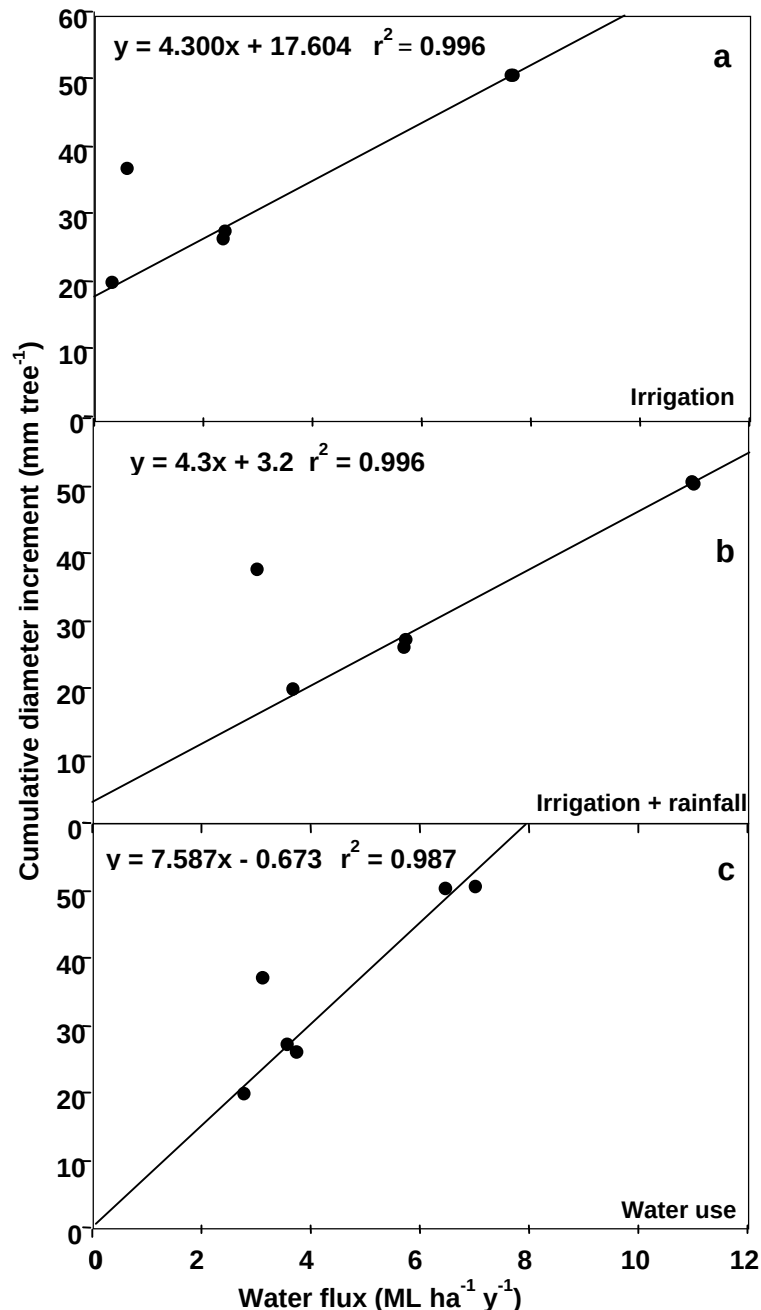


Figure 5.1 Correlations between cumulative diameter increment at Norwood Park after two years of irrigation and (a) mean annual volume of irrigation, (b) mean annual irrigation+rainfall, and (c) water use as determined from changes in soil water content. Each point represents a replicate plot in the N, O and H treatments. The outlying point is the N2 plot which had access to water in the adjacent irrigation channel, or perhaps to groundwater.

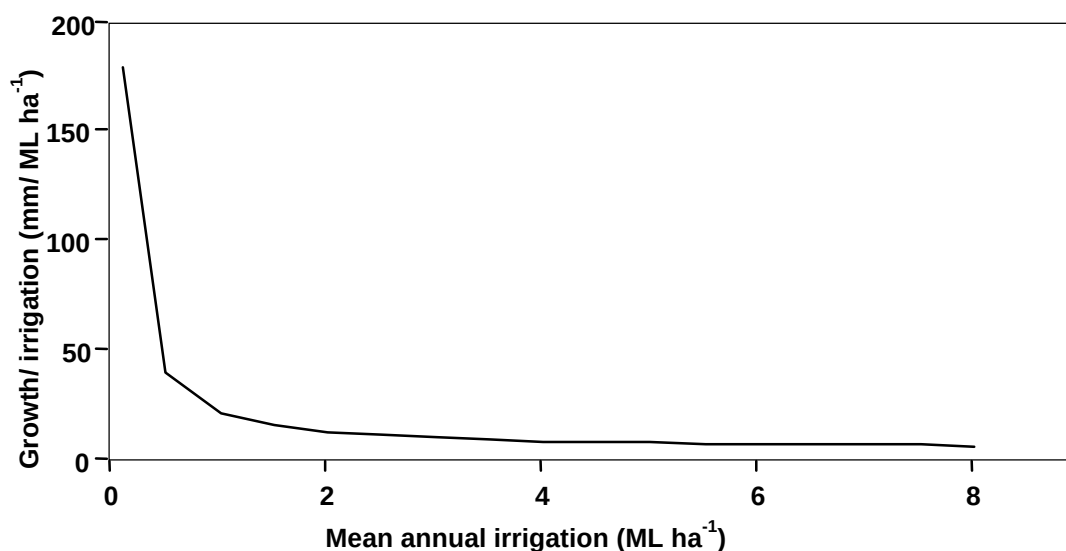


Figure 5.2 The relationship between irrigation use efficiency (ratio of growth: irrigation, G/I) and the mean annual irrigation applied at Norwood Park. The equation to the curve is: $G/I = 4.3 + 17.6/I$, and was derived from the line in Figure 5.1a.

The above results give some insight into relationships between annual rates of irrigation and growth. Results from dendrometer bands can also be used to study the short-term patterns of growth and responses to irrigation. Figure 5.3 shows mean daily diameter increments, and cumulative diameter increment per tree since the commencement of monitoring.

The effect of irrigation was short lived (Fig. 5.3a). In the 1997/98 irrigation season, for example, growth in the O treatment responded markedly to irrigation or significant rain, but decreased to low levels in the following month. Growth in the H treatment was apparently sustained by irrigation in the 1997/98 season, but by monitoring monthly we were not sure of the exact duration of the growth response. For the 1998/99 season we therefore increased the frequency of monitoring to fortnightly. It was shown that the response to irrigation was immediate and large for the first fortnight, but that growth rapidly decreased during the second fortnight, sometimes to negative values (Fig. 5.3a). During the non-irrigation period, growth in all plots converged to the same values. Thus it appears that growth would benefit from irrigation at least once every 14 days, and possibly more frequently.

During the two-year period growth in the H treatment was about twice that in the O treatment, but had received about three times the amount of irrigation (Fig. 5.3b), confirming the decrease in irrigation use efficiency as irrigation volume increases (Fig. 5.2).

5.2 Satellite sites

There was wide variation in growth among satellite sites reflecting differences in site conditions (mostly soil type), and previous irrigation management. Growth at Karawatha was good, the 4-y mean annual volume increment exceeding $20 \text{ m}^3 \text{ ha}^{-1}$ (Table 5.2). In part this reflects not only the good soil at this site but also that the trees were well irrigated during the first 2 years. Although we do not have good records of the volumes applied, the plantation received about 11 irrigations during the second year of growth. Growth at Billinudgel was poor, probably reflecting the very shallow heavy clays at the site and hostile chemical and physical conditions in the subsoil (Fig. 2.5). Growth at Baxters was intermediate between trees at Karawatha and Billinudgel, and better than growth at Norwood Park.

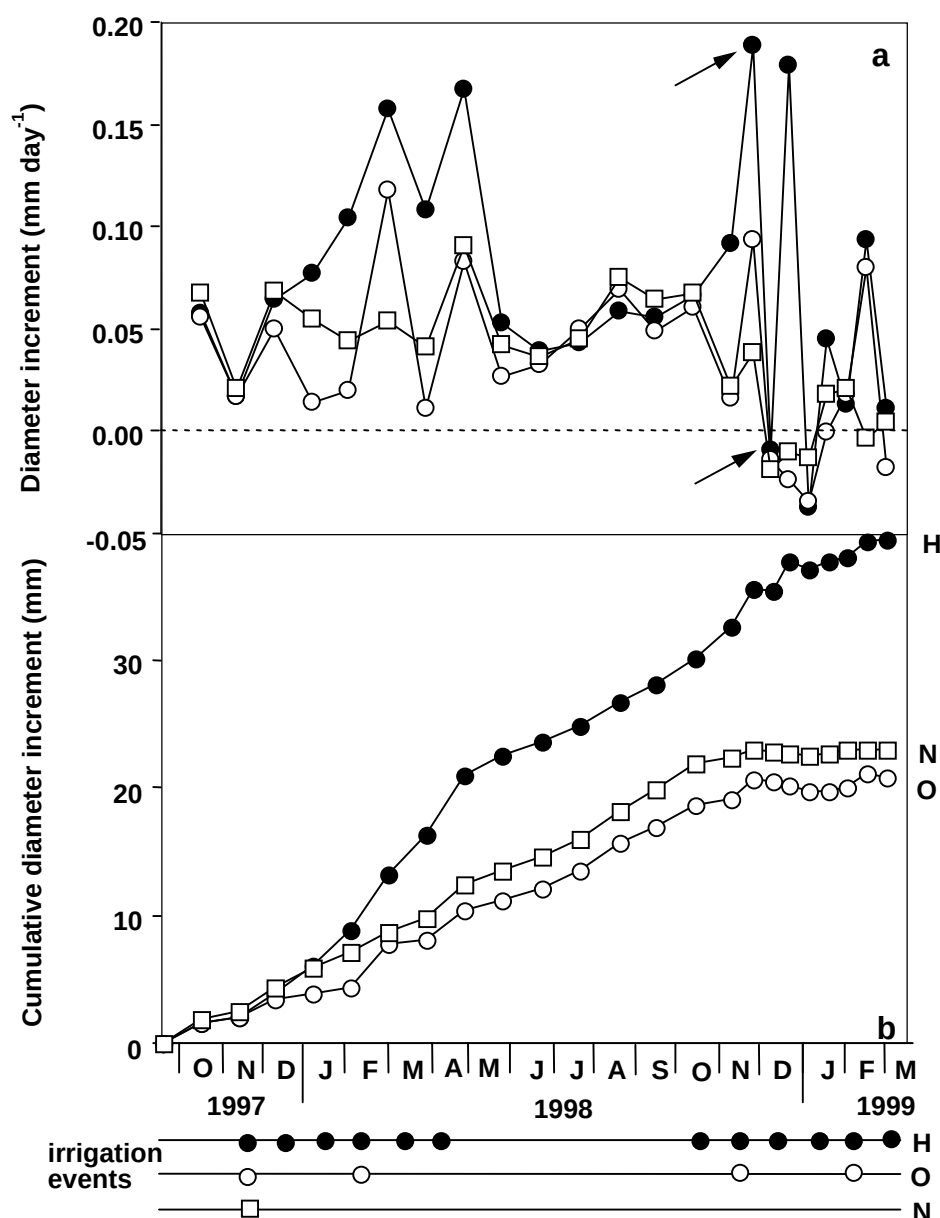


Figure 5.3 (a) Mean daily diameter increments, and (b) cumulative diameter increments as measured by dendrometer bands at Norwood Park, in relation to irrigation event. Measurement intervals were monthly until November 1998 and fortnightly thereafter. Generally there is a large response to irrigation during the first 14 days after irrigation (top arrow), followed by a significant decrease in growth during the second 14 days (bottom arrow).

Figure 5.4 illustrates patterns of diameter growth measured every two weeks in satellite trials during the irrigation season of 1998/99. All sites were irrigated twice (November and January) except for Baxters which was irrigated only in November. All plantations responded markedly to irrigation, particularly in January (Fig. 5.4a). The growth response was sustained for two weeks or less, dropping to low levels by six weeks after irrigation.

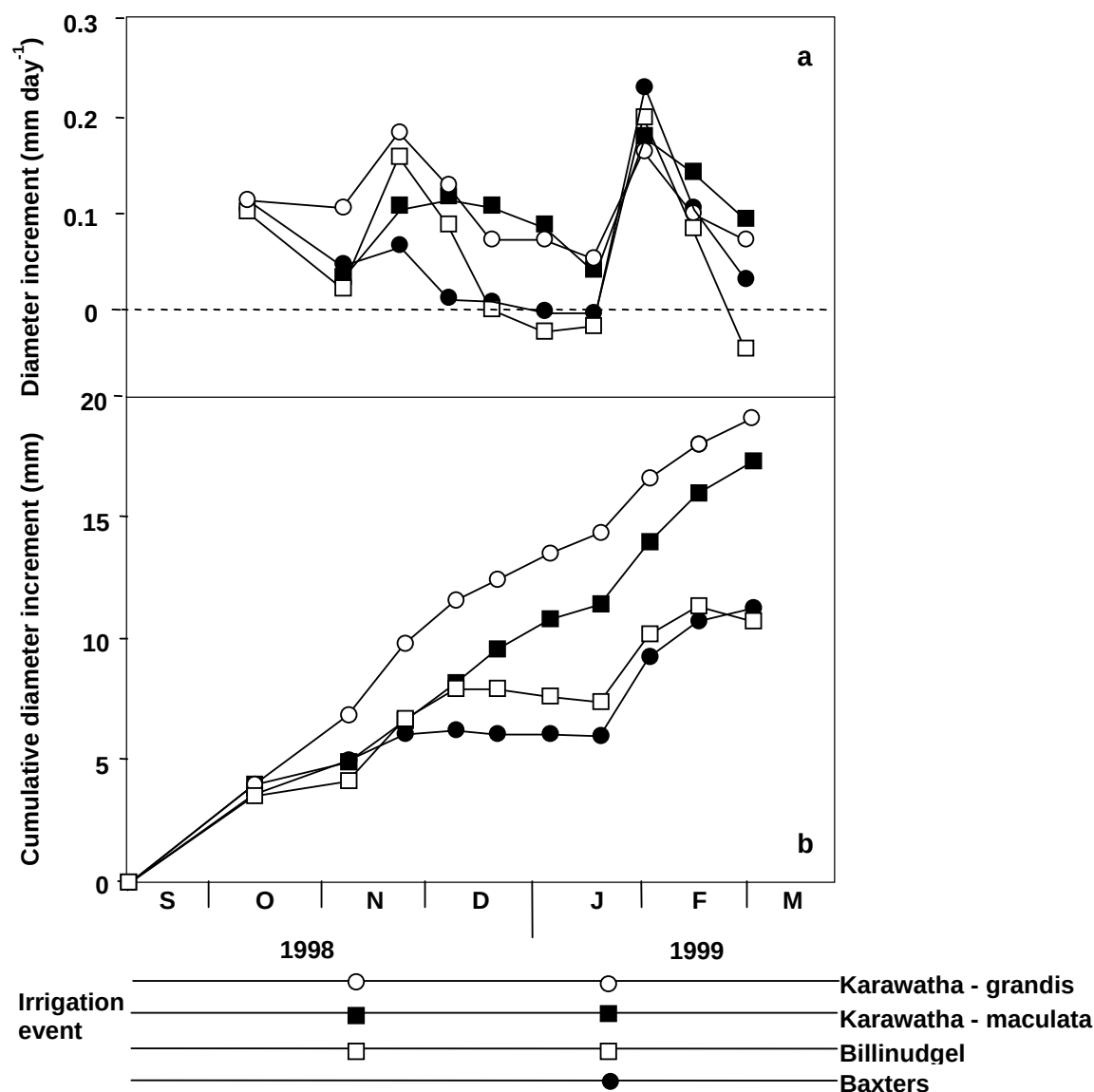
During the interval between November and January when trees received no irrigation, diameter growth at Baxters and Billinudgel declined to zero or less, while trees continued to grow at Karawatha (Fig. 5.4a). This indicates that trees at the former sites relied solely on irrigation or rainfall for sustained growth whereas at Karawatha trees had access to water stored deep in the soil profile, or to groundwater. These issues and further evidence for groundwater uptake are explored in the next section. At the very least, results confirm that trees on shallow clayey soils would benefit from frequent irrigation in order to maximise growth. In the previous section it was shown that frequent irrigation would increase losses of water to run-off and deep drainage, and so small volumes should be

applied. On the deep sandy loams with a deeper effective rooting depth, irrigation can be less frequent and the volumes in each irrigation event larger.

Figure 5b shows cumulative diameter growth and clearly reinforces the increased growth benefit derived when trees have prolonged access to stored irrigation water, or perhaps access to groundwater. At the end of the irrigation season cumulative growth at Karawatha was nearly twice that of trees at Billinudgel and Baxters despite only two irrigations having been applied.

Table 5.2 Summary volume growth among treatments at satellite trials

Site	Volume (m ³ ha ⁻¹)			
	At three years	Year four CAI	MAI	
			At three years	At four years
Baxters	33.2		11.1	
Billinudgel	6.4	7.2	2.1	3.4
Karawatha-grandis	54.1	50.5	18.0	26.1
Karawatha-maculata	48.4	40.7	16.1	22.3



6. Groundwater Use

Although our study was in irrigated plantations, the approach described here relates just as much to dryland (non-irrigated) forestry where there is serious impact of groundwater rise and associated salinity on land management. Rising watertables and associated salinity occur where there is an imbalance between inputs of water (rainfall or irrigation) and outputs (evapotranspiration, lateral flow and deep drainage). Increasing groundwater discharge through establishment of tree plantations can restore the balance between groundwater recharge and discharge under irrigated as well as dryland conditions. This section describes methodologies used to formulate a strategy for groundwater control in Riverine Plain soils.

There has been comparatively little research in the past to estimate the contribution by shallow groundwater to growth and productivity of tree plantations under rainfed and irrigated conditions growing over varying soil types. Recent advances in sap flow measurement (Hatton *et al.* 1995) in conjunction with traditional water balance studies can be used to estimate the extent to which plantations in our study sites relied on groundwater, and assess the effect of site (soil) conditions and tree species on groundwater uptake. Evidence for groundwater extraction is based on both direct and indirect measurements of soil water fluxes. These are described below.

6.1 Indirect assessment of groundwater extraction

Measurements taken to qualitatively assess groundwater extraction by trees were:

- Changes in soil water content – fortnightly;
- Soil water potential – during four irrigation cycles;
- Tree water stress - during an irrigation event;
- Watertable depths – fortnightly; and
- Tree growth – fortnightly.

Details of these measurements are described in Sections 3 and 4.

6.1.1 Soil water extraction

There were differences among sites in patterns of soil water extraction (Fig. 6.1). Changes in soil water content at different times of the year indicate the degree of root activity throughout the soil profile. The zone of root zone activity at Norwood Park was confined to the upper 1.0-1.2 m of soil whereas at Karawatha it extended to 2.8 m depth, just above the watertable. At Billinudgel, soil water extraction was also confined to the upper 1 m, whereas at Baxters there was some extraction down to about 2 m.

6.1.2 Leaf water stress

During one irrigation cycle at Norwood Park, pre-dawn leaf water potentials of trees in the three treatments were measured prior to the day of irrigation and continued until two days after irrigation. Trees were always stressed prior to irrigation (see Fig. 4.4 in Section 4). All three treatments at Norwood Park had low pre-dawn water potentials (ψ_p) on the day prior to irrigation, indicating water stress. Once irrigated, however, the trees in the ‘O’ and ‘H’ treatments recovered to a higher ψ_p , indicating that these trees exclusively relied on irrigation water for transpiration.

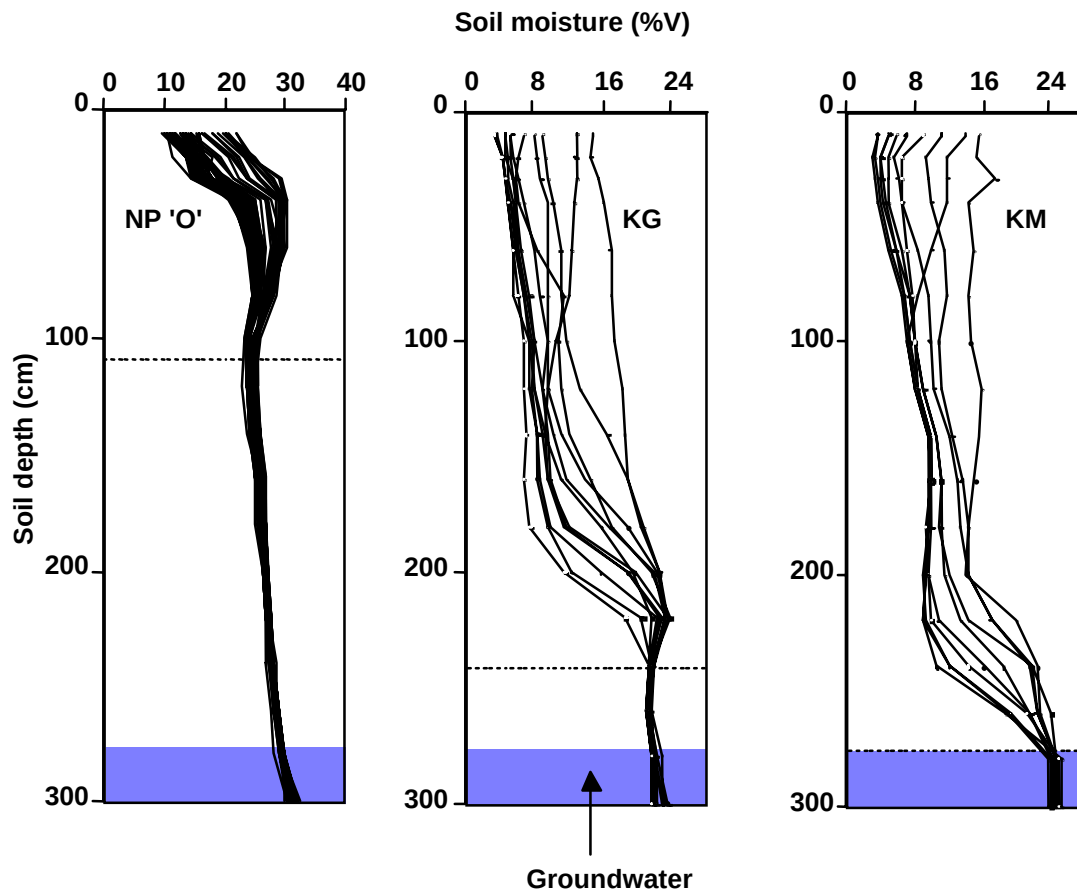


Figure 6.1 Patterns of soil water extraction pattern with depth at Norwood Park (NP 'O') treatment, and at Karawatha under *E. grandis* (KG) and *C. maculata* (KM) during the 1998-99 growing season.

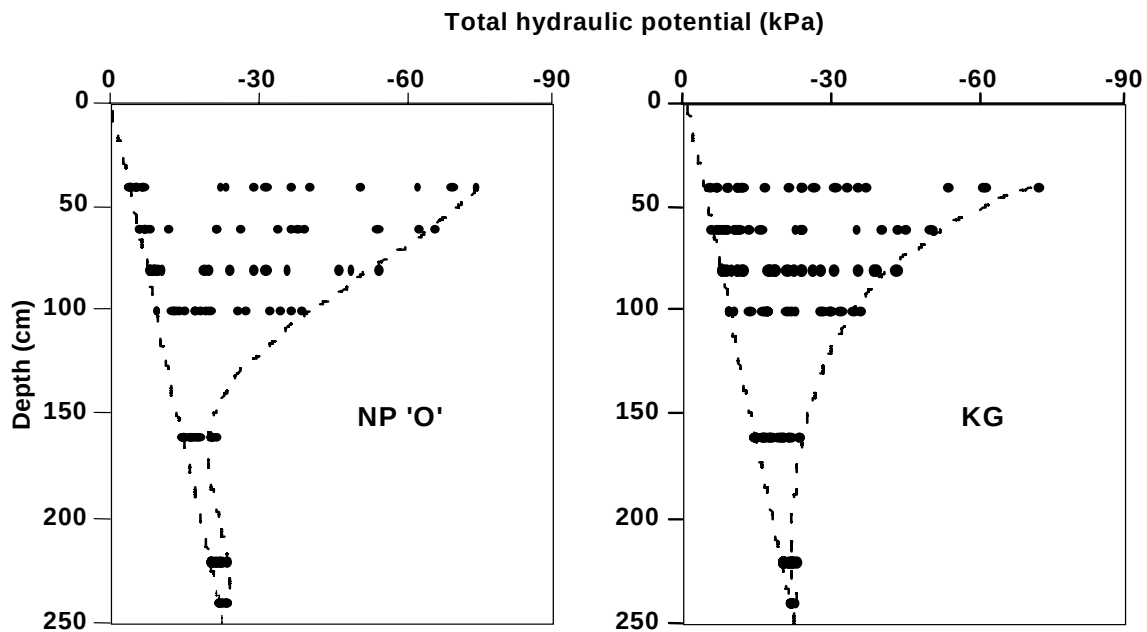


Figure 6.2 Changes in total hydraulic potential with depth and time after irrigation at Norwood Park (NP 'O') and Karawatha (KG). The dotted lines indicate the boundaries of the highest and lowest hydraulic potential measured during several irrigation cycles. Soil at Norwood Park shows an upward potential gradient to 150 cm depth whereas at Karawatha the upward gradient ends to 250 cm depth.

6.1.3 Soil water potential

Measurements of soil hydraulic potential taken during the end of irrigation cycles showed that at Norwood Park there was an upward gradient for water movement at depths above 1.5 m and below this water drained (Fig. 6.2). At Karawatha, there was upward movement of water throughout the soil profile. Therefore depth of the active root zone at Norwood Park was less than 1.5 m; at Karawatha it extended to 2.7 m, and at Baxters it was intermediate between that at Norwood Park and Karawatha.

Differences in depths of the active root zone among sites appeared to be related to soil type. Norwood Park and Billinudgel had the most difficult conditions for root growth (alkaline, sodic, saline and massive clay sub-soils), whereas Karawatha had the most favourable soil conditions (deep sandy loams with neutral properties), with Baxters being intermediate.

6.1.4 Watertable depths

Watertable depths at all sites fluctuated seasonally between 2.8 and 3.0 m from the soil surface (Fig. 6.3), the rise of watertable coinciding with periods of peak irrigation. During the summer of 1998-99, there was a pronounced decline in watertable depth from 2.8 to 3.5 m under the *C. maculata* plantation but not under the *E. grandis* plantations at Norwood Park or Karawatha, indicating a higher rate of uptake of groundwater under *C. maculata*.

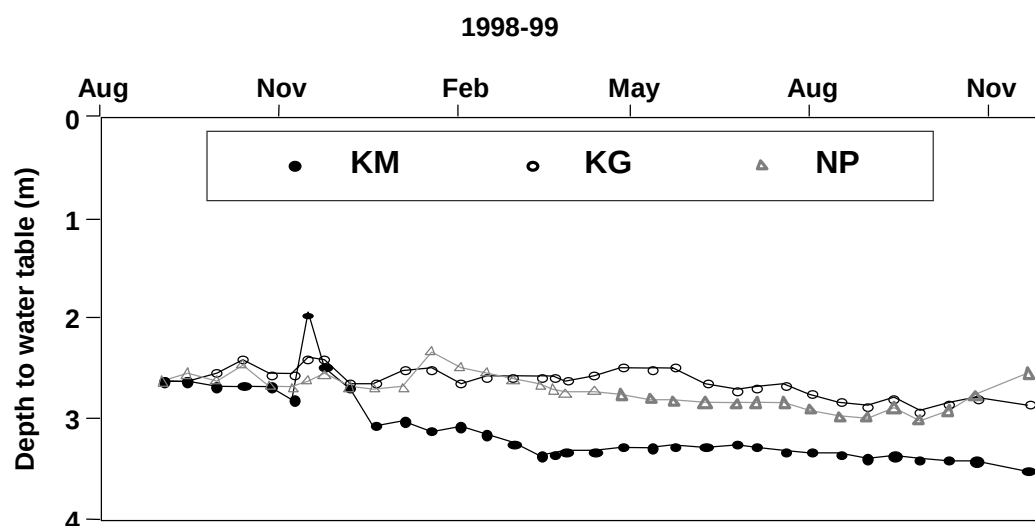


Figure 6.3 Changes in depth to watertables at Norwood Park (NP) and under Karawatha *E. grandis* at Karawatha (KG) and *C. maculata* at the same site (KM) during the 1998-99 season

6.1.5 Soil moisture depletion

Fortnightly soil moisture measurements at lower depths in the soil profile can also indicate the extent to which groundwater extraction lowers the watertable at times when evaporative demand is high. This depletion was pronounced only under the *C. maculata* plantation (Fig. 6.4), where soil moisture content at 2.6-2.8 m depth decreased from 20% in July 1998 to 12% in October 1999. In the *E. grandis* plantations at Norwood Park and Karawatha, soil moisture remained almost constant at 30% (Fig. 6.4).

6.2 Direct assessment of groundwater extraction

A combination of three methods (see Fig. 3.1 in Section 3) was used to estimate groundwater use by plantations. Total plantation water use, including transpiration from trees and weeds and evaporation from the soil surface, was estimated using a traditional water balance method. Transpiration by the trees was estimated from sap flow measurements. In addition to these methods, the Penman-Monteith evapotranspiration equation was used to calculate maximum plantation water use under the prevailing climate in non-water-limited conditions.

Comparison of water use estimated by soil water balance (ET) and sap flow sensors (T) enabled sources of water extracted by plantations to be inferred. Figure 6.5 compares cumulative plantation water use estimated by: (a) the soil water balance method, and (b) sap flow measurements, in the four satellite trials during 1998-99. With the exception of Karawatha, plantation water use estimated by the soil water balance method is consistently higher than or equal to tree transpiration estimated from sap flow measurements. If trees are not extracting groundwater, total ET estimated by water balance will be higher than T alone, as ET includes evaporation of water from the soil surface and transpiration from weeds, whereas sap flow is measured only in trees.

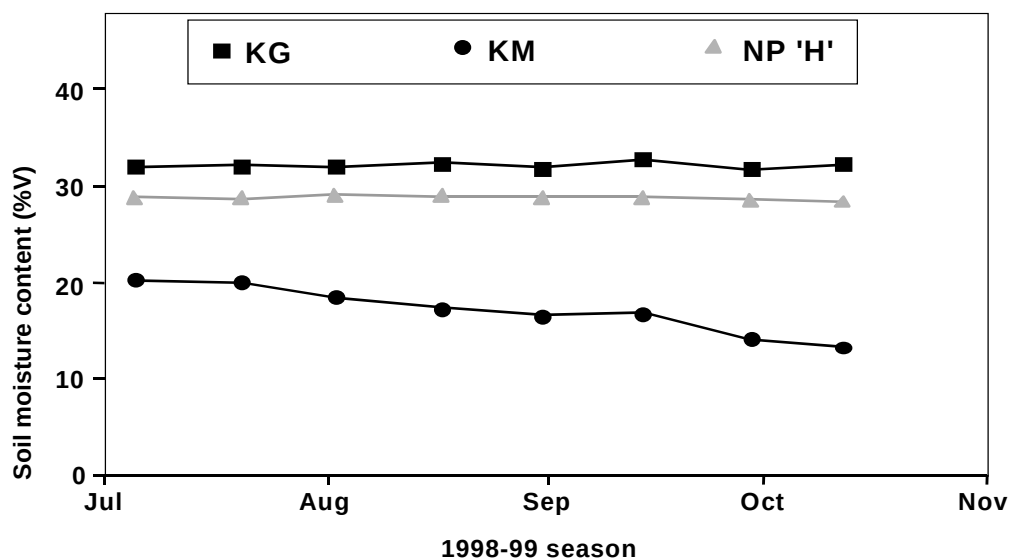


Figure 6.4 Changes in soil moisture content with time at 2.6 m depth in the *E. grandis* plantation at Norwood Park and in the *E. grandis* and *C. maculata* plantations at Karawatha during 1998-99 season.

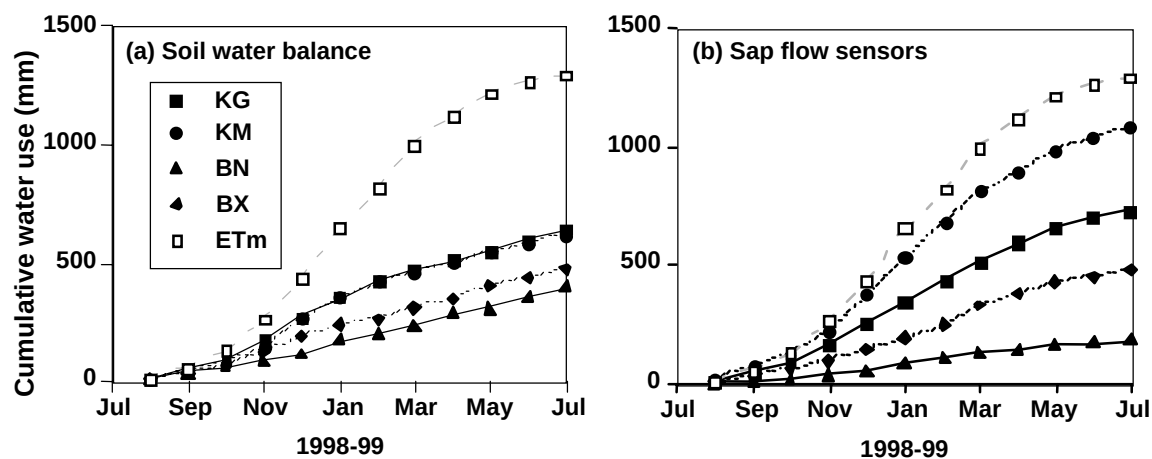


Figure 6.5 Cumulative water use for the four satellite trials estimated by: (a) soil water balance, and (b) sap flow measurements. Maximum evapotranspiration (Etm and which includes evaporation from soil surface) for a four-year-old *E. grandis* plantation at Deniliquin for the 1998-99 season was estimated using the Penman-Monteith evapotranspiration model.

Comparison of fortnightly mean tree transpiration and plantation water use (ET) of the 'H' treatment at Norwood Park and *C. maculata* at Karawatha (Fig. 6.6) showed contrasting relationships. Regression lines fitted through the origin indicated that transpiration at Norwood Park accounted for 78% of ET. For *C. maculata*, there was no such relationship, but the regression line indicated that, on average, these trees extracted groundwater at the rate of 2 mm day⁻¹.

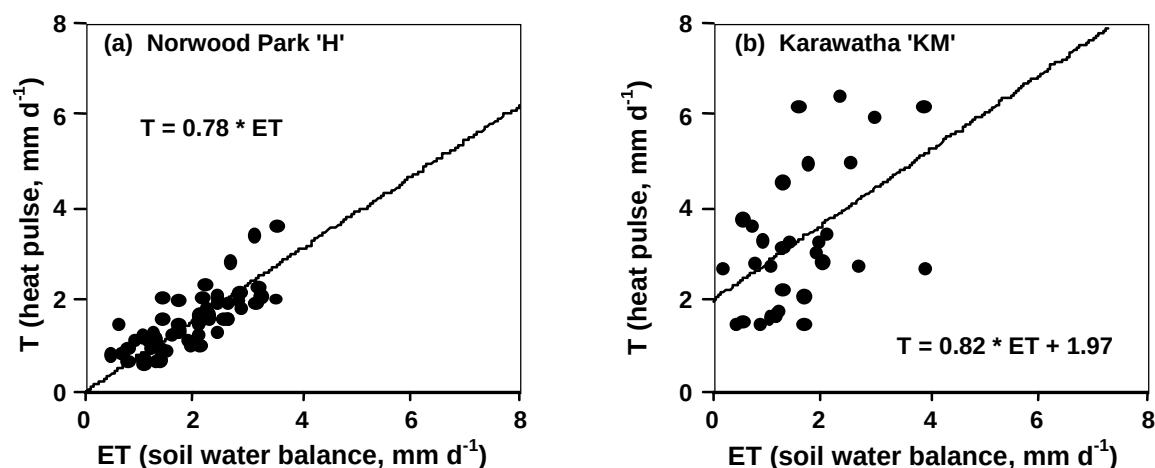


Figure 6.6 Relationship between estimates of tree transpiration obtained by the heat pulse method (T, mm d⁻¹) and of evapotranspiration obtained by soil water balance at: (a) 'H' treatment at Norwood Park, and (b) *C. maculata* at Karawatha.

The groundwater contribution to transpiration during the 1998-99 and 1999-2000 growing seasons was estimated for all sites (Table 6.1). Because *C. maculata* had high rates of transpiration (close to ET_m), it was assumed that these trees were growing under non-water limited conditions. Hence in Table 6.1a, evaporation of water from the soil surface (E) was calculated as ET_m - T, being 213 mm. Transpiration derived from soil water (T_{sw}) was calculated as ET - E, which for *C. maculata* was 411 mm, and transpiration derived from groundwater (T_{gw}) was calculated as T - T_{sw}, which for *C. maculata* was 673 mm.

For Billinudgel and Norwood Park, where it appears roots are not accessing groundwater, E was estimated to be 118 mm for Norwood Park and 214 mm for Billinudgel. Because soil surface conditions at Norwood Park and Baxters were similar, evaporation of water from these soil surfaces was assumed to be the same (118 mm).

The above calculations show that at Karawatha, the *E. grandis* and *C. maculata* trees respectively obtained 41% and 62% in 1998-99 and 73% and 82% in 1999-2000 of their total transpiration from groundwater, while at Baxters it was 25% and 29%. Plantations at Norwood Park and Billinudgel did not appear to be using groundwater.

6.3 Implications for groundwater extraction

This study has confirmed the utility of using measurements of sap flow, soil water balance and climate to calculate groundwater extraction by trees. At Norwood Park and Billinudgel there was no evidence of groundwater extraction by the trees, even though the watertable was only 2.8 m below the soil surface. It is likely that unfavourable soil physical and chemical properties had restricted the growth and penetration of tree roots to less than 1.2 m depth. At Baxters, trees were beginning to grow roots to deeper soil layers, patterns of soil water extraction indicating that the active root zone was 2 m deep. With a watertable at 2.7 m, some of the tree roots may be within the capillary fringe and thus extracting groundwater. It was estimated that about 119 mm (25% of total transpiration) was extracted from the shallow watertable during the 1998-99 season at Baxters. Karawatha showed clear evidence of groundwater use in both *E. grandis* and *C. maculata* plantations. With good soil and deep roots active near the watertable, high rates of water use were sustained, even though the plantation was only irrigated three times during the year. At this site, tree water use was much greater than could be accounted for by changes in soil water, especially in *C. maculata*, indicating substantial use of groundwater. This conclusion is supported by patterns of soil water extraction, and total hydraulic potential measurements, which showed extraction at all depths above the watertable.

Table 6.1 Maximum evapotranspiration (ETm), evapotranspiration estimated by soil water balance (ET) and plot transpiration estimated using sap flow sensors (T) for Norwood Park (NP) and the four satellite trials for 1998-99 and 1999-2000 growing seasons; Karawatha (KG and KM with *E. grandis* and *C. maculata*), Billinudgel (BN) and Baxters (BX). Evaporation of water from the soil surface (E) was estimated for KM and KG plots as described in the text. T was partitioned between two sources of water supply - water extracted from the soil (Tsw), and water extracted from groundwater (Tgw). Groundwater (GW) contribution to tree transpiration was estimated as the ratio of Tgw to T.

(a) 1998-99

Water (mm)	KG	KM	BN	BX	NP - 'H'
ETm	1185	1297	1013	1102	1102
ET	644	624	402	481	515
T	734	1084	189	482	397
E	213	213	214	118	118
Tsw	431	411	189	363	397
Tgw	304	673	0	119	0
GW contribution	41%	62%	0	25%	0

(b) 1999-2000

Water (mm)	KG	KM	BN	BX	NP - 'EF'
ETm	1256	1256	1016	1146	1146
ET	458	463	428	497	677
T	615	963	251	387	439
E	293	293	177	223	238
Tsw	165	170	251	275	439
Tgw	450	793	0	113	0
GW contribution	73%	82%		29%	

These studies show that careful selection of sites and species, and proper design and establishment of plantations, are required if farm forests in this region are to be used successfully to ameliorate land degradation caused by rising watertables and associated salinity, and to maximise growth.

Irrigation of rice and other agricultural crops has been a major contributor to the rapid rise in water tables in this region. Although there are stipulations in the region that confine rice crops to only shallow heavy clay soils (in order to restrict drainage), Dwyer (1992) estimated that the average recharge through deep drainage from rice fields is 2-3 ML/ha during the irrigation season. This estimate has also been corroborated by work carried out independently by CSIRO Land and Water (Humphreys *et al.* 1994). Total drainage from 70,000 ha of rice fields would thus be about 140,000 ML and would approximate the amount needed to be extracted from groundwater every year if water table rise in the region were to be arrested.

Based on estimates of water balance, groundwater use by *C. maculata* growing under excellent site conditions (Karawatha site), our results indicate that the total recharge from 70,000 ha of rice irrigated in the region would provide adequate water for about 14,000 of tree plantations (as a continuous crop) while maintaining a groundwater balance. These plantations would need to be uniformly distributed on light textured soils around prior streams to minimise excessive draw-down of the watertable beneath the plantations.

The above prediction is based on several assumptions:

- (i) that 14,000 ha of suitable land is available around prior streams for tree plantations in this region,
- (ii) transmissivity of the Upper Shepparton aquifer is high enough to transport drainage water from rice fields to the tree plantations, and

- (iii) groundwater within these prior streams is generally fresh or slightly saline ($< 1 \text{ dS m}^{-1}$) and build-up of salinity within the root zone would be flushed out by fluctuating watertables. These assumptions are based on various internal reports from Department of Land and Water Conservation at Deniliquin and from personal communication from other researchers (hydrogeologists, rice agronomists, etc.) in the region. It was not within the scope of this study to verify these assumptions, but would be the subject of on-going work.

Where plantations use a substantial amount of groundwater, different irrigation strategies are required as the stand develops. Frequent irrigation in small volumes during the first two years of growth followed by gradual tapering to stop irrigation during the fourth year encourages the trees to develop deep roots and to access water from the capillary fringe of the watertable.

Careful selection of sites and species, and proper design and establishment of plantations are also required. Factors to consider in site selection are:

- Proximity to prior streams or localised sandy aquifers;
- Soil physical conditions;
- Watertable depth; and
- Salinity of subsoil and groundwater.

Based on the results from this study we recommend that prior streambeds be targeted for extensive planting with *C. maculata*.

7. Salinity

Under irrigation the risk of salinity comes from either:

- Irrigation with saline water that, if not properly managed, causes salt to accumulate in the root zone, decreasing growth (some drainage waters would be an example); and
- Uptake of saline groundwater that, under some soil, climatic and management conditions can cause accumulation of salts around deeper roots, again inhibiting growth.

We used sequential coring of soil to nearly 2 m depth at Norwood Park to monitor changes in salinity. Changes in soil salinity, both within and across treatments, at Norwood Park (Figs 7.1 and 7.2) were variable and there were no treatment effects or long-term trends. Soil had an average EC_e of 0.7 dS m^{-1} in the surface 1 m that progressively increased to 3 dS m^{-1} in the 1-2 m layer. Soil salinity greater than 4 dS m^{-1} in saturation paste extract (EC_e) can restrict growth of *E. grandis* (Coffs Harbour provenance) (Falkiner and Smith 1997). An additional constraint to plant growth is the presence of shallow (3 m) and saline groundwater (11.2 dS m^{-1}).

An increase in soil salinity in the surface 0.5 m of the 'H' treatment from an average of 0.58 in May 1998 to 0.92 dS m^{-1} in May 1999 resulted from irrigation with drainage water during the 1998/99 season. Drainage water was four-times more saline than channel water (Table 7.1) and was applied more frequently in the 'H' treatment. Inputs of total dissolved salts from irrigation were small ($160 \text{ kg ha}^{-1} \text{ y}^{-1}$) on the 'O' treatment, due to the low mean salinity (0.25 dS m^{-1}) of irrigation water and so salinity in surface soil did not increase. In addition the sodium absorption ratio (SAR), an indicator of the sodicity hazard, is low (1.3) and pH is close to neutral.

Salinity in the sub-soil (1-2 m) significantly ($P>0.05$) increased from May 1998 to May 1999 in the 'O' treatment. Smaller but non-significant increases in sub-soil salinity during the same period are more evident in the 'N' and 'H' treatments. Collections during the irrigation season (December 1997) and also in May 2000 (AF and EF treatments) indicate that sub-soil salinity was variable and had not consistently increased or decreased from September 1997 to May 2000.

Soil salinity, especially in the surface, was increased by irrigation with slightly saline discharge water but subsequent irrigation with channel water reduced salinity to normal levels.

There was little significant change in soil salinity at Norwood Park. This was due to:

- Treatments were mainly irrigated with non-saline channel water; and
- Uptake of groundwater was insubstantial.

Where irrigation water is of moderate salinity (e.g. $>2 \text{ dS m}^{-1}$) this will need to be managed through use of appropriate over-irrigation, to leach salts from the root zone. We note that *E. grandis* may be particularly sensitive to salt accumulation, even when irrigated with water of moderate salinity (Myers *et al.* 1998).

Table 7.1 Salinity, pH and sodium absorption ratio (SAR) of channel (n=9) and drainage (n=7) irrigation water applied at Norwood Park from November 1997 to December 1999.

Water type	Salinity (dS m^{-1})	SAR	pH
Channel	0.11	0.9	7.6
Drainage	0.43	3.2 [†]	7.7
Mean	0.25	1.3	7.7

[†] single determination

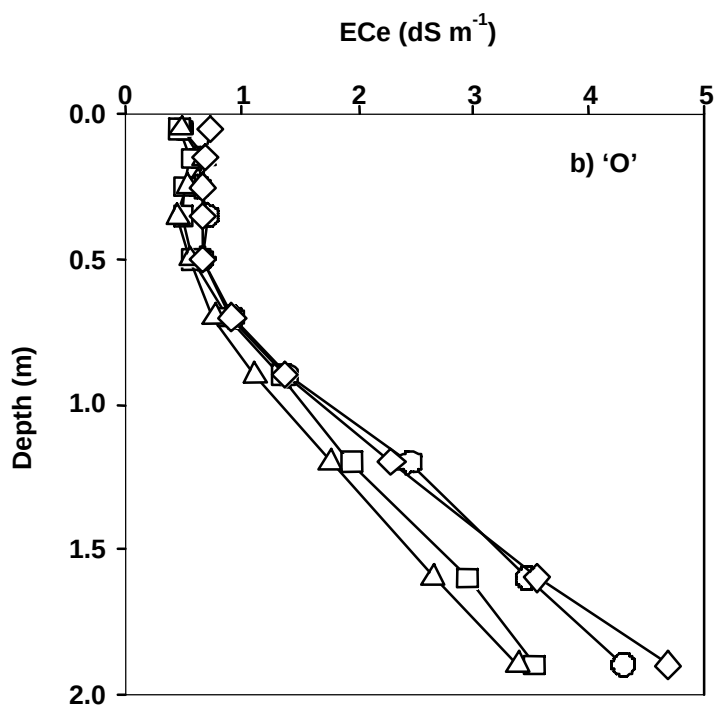
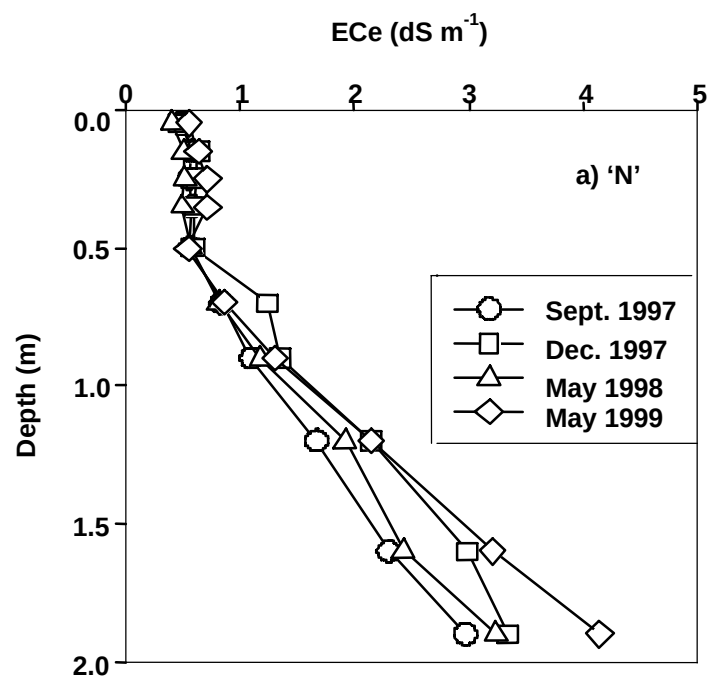


Figure 7.1 Changes in soil salinity at Norwood Park in the (a) 'N' and (b) 'O' treatments from September 1997 to May 1999.

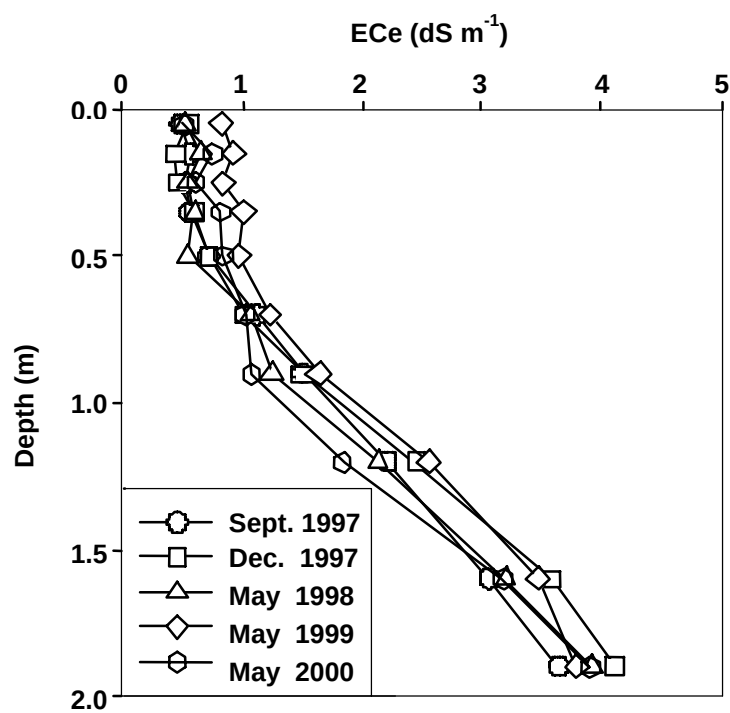


Figure 7.2 Changes in soil salinity at Norwood Park in the 'H' treatment from September 1997 to May 1999 and EF/AF treatment in May 2000.

8. Synthesis and Conclusions

Farm forestry in irrigated areas such as Deniliquin offers an opportunity for growing productive plantations but development of large-scale commercial ventures is still limited by:

- The high demand for water to maximise growth of plantations;
- The relatively high cost of water, and the likelihood of an increased cost and decreased availability of water in the future;
- Lack of appropriate guidelines for conservative use of water in irrigated plantations, and expected rates of growth per ML of water applied; and
- Lack of knowledge for the potential of plantations to use groundwater under varying site and species conditions, and expected rates of growth enhancement.

Results from this series of experiments have gone some way to addressing these impediments. In particular, it is important to match species selection and irrigation strategy to the site (soil type) for maximum environmental and economic benefit. Results and recommendations can be usefully separated according to soil type and groundwater quality:

Shallow clayey soils (alkaline, saline, sodic massive clays in B horizon (>0.5 m depth); saline groundwater at 2.5-3 m)

- Harsh soil conditions limit roots to the surface 0.5 m of soil, effectively defining these as ‘shallow’ soils;
- Irrigation efficiency is low, 25% to 50% of the water applied remaining in soil available for transpiration, the remainder being lost to run-off, evaporation from ponded water or subsequently from soil, or to deep drainage;
- Plantation growth is proportional to the total amount of water received (irrigation + rainfall);
- Growth response to irrigation generally lasts less than 14 days;
- There is little use of groundwater as determined from water balance studies and changes in soil hydraulic properties; and
- Plantations have little or no effect on soil salinity, measured throughout the profile down to the watertable.

On these soil types:

- Irrigation needs to be frequent and in small amounts;
- There should be no expectation that plantations will use significant amounts of groundwater; and
- Growth rates will be modest depending upon the severity of soil conditions; highly saline sub-soils may restrict volume growth to less than $5 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$.

Deep sandy loam soils (neutral soil properties down to relatively fresh groundwater at 2.5-3 m).

- Roots penetrate to greater depths in these soils, proliferating in the capillary zone just above the watertable;
- Irrigation efficiency is thus higher than in shallow clayey soils, more of the water being stored in soil where it can be accessed by roots; and
- There is substantial use of groundwater — as much as 80% of total plantation water use.

On these soil types:

- Irrigation can be less frequent, and applied at higher rates, than on heavy soils;
- It can be expected that plantations will use significant amounts of groundwater; and
- Growth rates will be excellent, perhaps exceeding $20 \text{ m}^3 \text{ ha}^{-1} \text{ y}^{-1}$ with little irrigation needed after the first two years.

Following these guidelines would maximise:

- Conservative use of irrigation water;
- Potential control of regional groundwater balances depending on extent of establishment; and
- Rates of plantation growth;
-

- thus achieving the objectives of multiple environmental benefit combined with growing plantations at commercial rates of growth.

The best outcome would be achieved if plantations of *C. maculata* (and to a lesser extent *E. grandis*) were planted on prior streambeds. Here, groundwater uptake would be maximised, trees would need the least irrigation, and rates of plantation growth would be high.

Some of the results behind these concepts are briefly synthesised below.

8.1 Irrigation strategies

Because trees are perennial crops, the annual irrigation requirement depends upon many factors including climate, soil properties and plant parameters such as leaf area index, depth of active root zone and stage of canopy development.

The potential water use is high ($PWU > 14 \text{ ML ha}^{-1} \text{ y}^{-1}$) in the low-rainfall regions of the southern Murray-Darling Basin ($< 600 \text{ mm}$), and probably is far greater than volumes that land managers and farmers would be willing to apply (Fig. 8.1). Although it is difficult to obtain good figures for the volume of water applied to plantations in the region, it seems that about 250 and 600 mm is about average for a well-established plantation. This relatively low rate in an environment of high evaporative demand has implications for plantation productivity. Most plantations will need to be irrigated at higher rates to achieve economic rates of growth for conventional forest products unless there is clear evidence of groundwater extraction.

The economic sustainability of using high volumes of water is also doubtful and this can be demonstrated using an economic model to assess the net cost and returns from irrigated tree plantations in this region.

Our results indicate that broad-scale flood irrigation is highly inefficient for tree plantations. Even when irrigation water was ponded to prevent run-off, only about 50% of applied water remained in the root zone, the remainder being evaporated or drained.

Depth of the active root zone varied markedly with soil type and this will determine the irrigation strategy employed. On massive clay soils, with shallow root systems, frequent, light irrigation will maximise irrigation application efficiency. While evaporation will be increased by such a strategy, there will be a greater reduction in deep drainage. On deep sandy loams with deep root systems, less frequent application of water in larger amounts should reduce evaporation, but will not increase deep drainage as the root zone has a much larger capacity to store water.

Tree growth can be divided into three phases for the purpose of determining appropriate irrigation strategies:

- Phase 1 – the period of establishment to up to two years from planting;
- Phase 2 - the period of canopy development between two and four years from planting; and
- Phase 3 - the period of growth, beyond four years from planting.

On deep sandy loams where trees have access to groundwater, we recommend the following strategy. Because of the effectively shallower root depth in Phase 1, trees would require frequent and small irrigations. WATLOAD2, an irrigation design model, estimates that during the first year of establishment, tree plantations would require 7 ML ha^{-1} on average (Fig. 8.1). During the second and third year the appropriate irrigation strategy is to encourage root penetration and growth into deeper soil layers. This can be achieved by reducing the irrigation requirement linearly from the second year to fourth year to permit irrigation with larger volumes at longer intervals. At the end of the fourth year the irrigation requirement can be reduced to $1 \text{ ML ha}^{-1} \text{ y}^{-1}$, to be used mainly as a store for extreme dry

periods, and also for leaching purposes if required. Depending on the salinity of groundwater, leaching can be applied to the tree plantation once every 2-3 years.

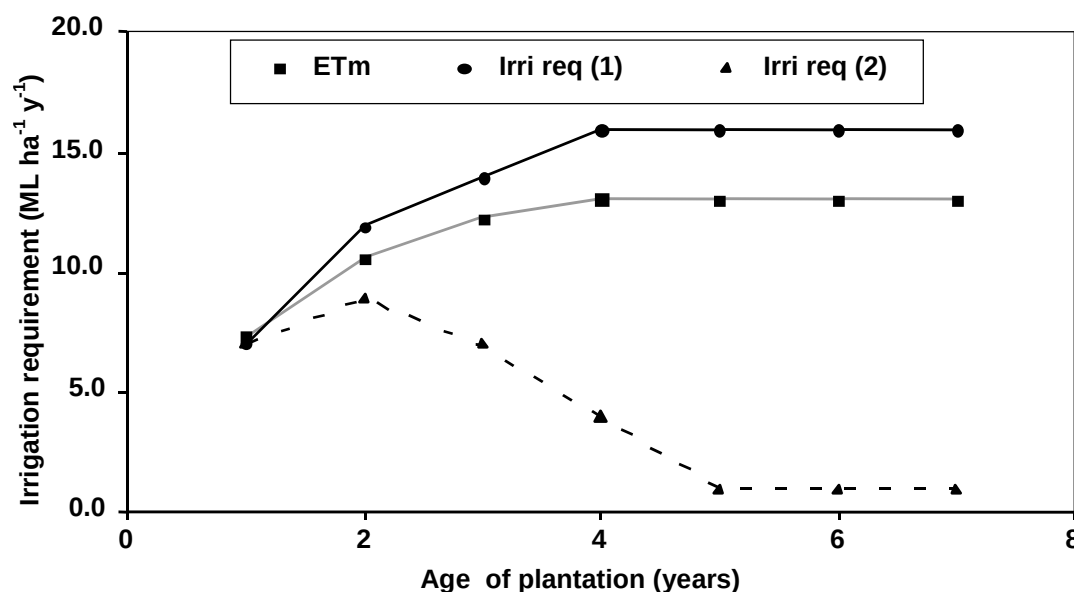


Figure 8.1 Flood irrigation requirement for tree plantations at different stages of growth under conditions of (a) non-groundwater use (Irri req (1)), and (b) groundwater use (Irri req (2)). Maximum evapotranspiration (ETm) was derived from the calibrated Penman-Monteith equation for *E. grandis* plantation. Irrigation requirements under the two different conditions were obtained from WATLOAD2 predictions using long-term climatic data for Deniliquin.

8.2 Groundwater uptake

This study has confirmed the utility of simultaneously using sap flow and soil water balance measurements to deduce groundwater extraction by trees. At Norwood Park and Billinudgel there was no evidence of groundwater extraction by the trees, even though groundwater was only about 2.8 m below the soil surface. Measurements of soil water, pre-dawn water potential and growth at Norwood Park indicate that it is likely that unfavourable soil physical and chemical properties had restricted the growth and penetration of tree roots to depths less than 1.2 m. At Baxters, trees were beginning to grow roots to deeper soil layers, the active root zone being about 2 m deep. With a watertable at 2.7 m, some of the tree roots may have been within the capillary fringe zone and thus extracting some groundwater. It was estimated that about 119 mm (25%) of total tree transpiration was extracted from the shallow watertable during the 1998-99 season at this site. Karawatha showed clear evidence of groundwater use. With good soil and deep roots active near the watertable, high rates of water use were sustainable even though the plantation was irrigated only three times during the year. At this site, trees continued to grow and the tree water use was substantially higher than could be accounted for by changes in soil water, especially in *C. maculata*, indicating use of groundwater. This is supported by patterns of soil water extraction and total hydraulic potential measurements, which showed extraction at all depths above the watertable. We estimate that over the 1999-2000 growing season, as much as 82% of total tree transpiration was sourced from groundwater under *C. maculata* and 73% from under *E. grandis*.

Based on water balance calculations, estimates of groundwater use by *C. maculata* trees, and other regional water balance studies, we calculate that the total recharge from 70 000 ha of rice plantations in the region would provide adequate water for about 14 000 of tree plantations (as a continuous crop) while maintaining groundwater balance. These plantations would need to be uniformly distributed around prior streams to minimise excessive draw-down of the watertable beneath plantations.

Apart from selection, proper site preparation is also essential for successful plantations within these prior stream areas. If roots cannot penetrate close to the watertable because of soil physical or chemical conditions, groundwater extraction will be limited. Flood irrigation is the preferred method of irrigation in this region for mainly historical reasons. Deep ripping and mounding would allow trees to establish a root system to encourage early extraction of groundwater.

In the Deniliquin region, a significant challenge remains to incorporate all this information into a management strategy. An effective and inexpensive method is needed to locate and map suitable sites in the region where trees can be grown to lower watertables and produce wood at economically viable growth rates. Even in the absence of a commercial wood production venture, strategic reforestation of areas of a farm could make a significant contribution to sustainable production.

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Appendix 1.1 Climatic data for Deniliquin

Long-term (>15 years) mean monthly climatic data for Deniliquin region: temperature (T), solar radiation (Rs), wind speed (W), relative humidity (RH), pan evaporation (Epan). Rainfall (R) is total for the month.

Month	T (°C)	Rs (W m ⁻²)	W (km d ⁻¹)	RH (%)	Epan (mm d ⁻¹)	R (mm)
January	22.6	547	281	52	9.90	20.6
February	22.3	520	263	54	9.29	25.9
March	19.5	465	236	61	6.98	23.6
April	15.5	363	198	71	4.10	27.5
May	11.8	253	177	83	2.04	44.9
June	9.0	208	203	88	1.30	42.5
July	8.2	216	213	89	1.28	46.8
August	9.1	301	234	84	2.05	34.5
September	11.4	385	248	81	3.30	31.7
October	14.6	464	252	72	5.34	30.9
November	17.9	506	268	61	7.79	26.1
December	21.1	520	281	55	9.24	38.2
Mean	15.2	396	238	71		
Total					1897	393

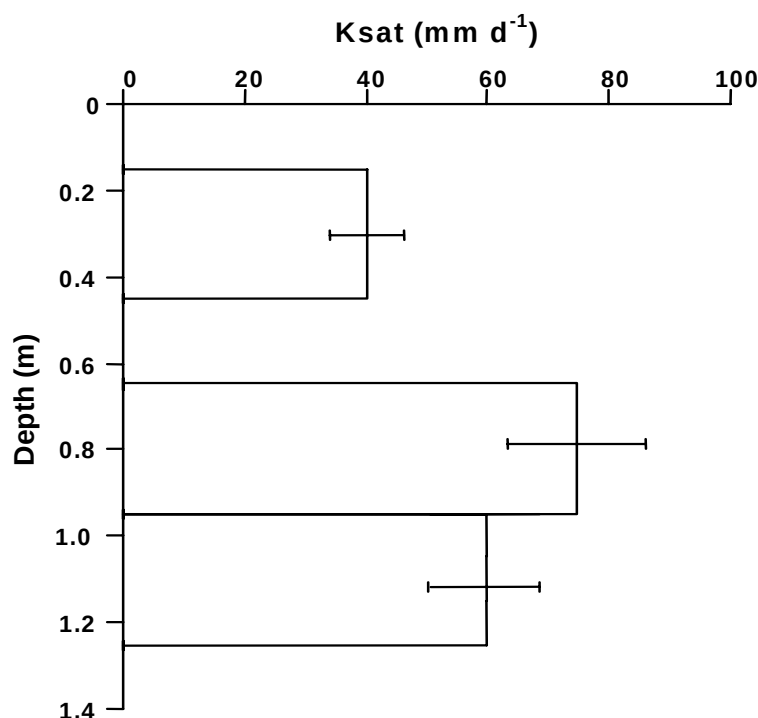
Appendix 1.2 Soil profile at Norwood Park

Summary of soil profile descriptions at Norwood Park

Horizon	Depth	Description	pH
A1	0.00 to 0.20 m	Clay loam, fine sandy	6.5
B21	0.20 to 0.30 m	Light clay	7.5
B22	0.30 to 0.40 m	Light medium clay	8.5
B3	0.40 to 0.60 m	Light clay	9.0
C	0.60 to 1.00 m	Sandy light clay	10

Appendix 1.3 Soil conductivity at Norwood Park

Mean saturated hydraulic conductivity across the site at Norwood Park, measured by borehole permeameter at 18 locations.



Appendix 1.4 Soil physical and chemical properties

Norwood Park

Soils are clay loams overlaying mottled medium clays (Appendix 2.2). Structure is massive and cracks of 5-10 mm are evident. Moist colours range from dark reddish brown to dark brown. Subsoils (>1m) are alkaline (pH in CaCl₂ >7.5, calcium carbonate present), sodic (SAR >12) and moderately saline (EC_e 3 dS m⁻¹). Depth to the saline groundwater (11.2 dS m⁻¹) is 3 m and the soil is moderately well drained.

Karawatha

Soils are single-grained loamy sands overlaying sandy loams. Moist colours range from dark reddish brown to yellowish red. Soil reaction is slightly acidic in the surface and neutral at depth. The profile is neither saline nor sodic. Soil is very well drained and depth to the non-saline groundwater is 3 m.

Baxters

Soils are poorly drained cracking light/medium clays overlaying mottled clay loams. Surface soil (0.2 m) is granular with deeper horizons having an angular blocky and lenticular structure. Moist colours range from dark brown to grey. Surface soils are slightly acidic (pH in CaCl₂ 5.5), slightly saline (0.45 dS m⁻¹) and marginally sodic (SAR = 4.7). Subsoils are alkaline (pH in CaCl₂ 7.5, gypsum, calcium carbonate and manganese nodules present), slightly saline (2 dS m⁻¹) and sodic (SAR = 10.4).

Billinudgel

Soils are very poorly drained cracking and mottled light clays overlaying mottled medium clays. Soil structure is weak subangular blocky/massive in the surface 0.5 m, and lenticular/massive in the

subsoil. Moist colours are dark greyish brown to greyish brown. Surface soils are slightly acidic (pH in CaCl_2 5.6), marginally saline (0.64 dS m^{-1}) and sodic ($\text{SAR} = 9.3$). Subsoils are alkaline (pH in CaCl_2 7.5, calcium carbonate present), moderately saline (3.4 dS m^{-1}) and sodic ($\text{SAR} = 19.0$).

At the Norwood Park site, the soil is a Brown Kandosol (New Australian Classification), or a Red-Brown Earth in the alternative terminology (Northcote Classification). Soil texture varies from a clay-loam in the surface horizon through a light-medium clay between 0.3-0.4 m to a sandy light clay between 0.6-1.0 m (Appendix 2.2). The field pH varies from near-neutral at the surface to pH 10 between 0.6-1.0 m.

Saturated hydraulic conductivity (K_{sat}) of the soil profile measured at the site using a borehole permeameter show that soil is slowly permeable, K_{sat} varying from 40 mm day^{-1} at 0.15-0.40 m to 75 mm day^{-1} at 0.9-1.2 m (Appendix 2.3).

Infiltration capacity of the soil, measured in 6 locations using a disc permeameter, ranged from 18 to 33 mm hour^{-1} with a mean of 24 mm hour^{-1} . These values for conductivity and infiltration are consistent with our observation that it takes about 3 days for 120-150 mm of irrigation to soak into the soil.

Norwood Park

Depth (m)	Horizon	Texture	Structure	Colour	pH (CaCl_2)	ECe^1 (dS m^{-1})	ESP^2 (%)	SAR^3 ($\text{mol}_\text{c} \text{ m}^{-3}$) ^{0.5}	TC^4 (%)	TN^5 (g kg^{-1})	TP^6 (g kg^{-1})
0-0.1	A1				5.5	0.5	4.6	2.7	1.39	1.09	0.27
0.1-0.2	A1	Clay loam	Massive	5YR3/2	5.4	0.6	4.4	3.6	1.29	1.03	0.28
0.2-0.3	B2				5.5	0.6	3.7	3.2	1.16	0.94	0.29
0.3-0.4	B2	Clay loam	Massive	5YR2/2	5.6	0.6	4.6	4.4	0.70	0.56	0.24
0.4-0.6	B3				6.4	0.6	8.1	6.9	0.49	0.56	0.23
0.6-0.8	C				7.1	1.0	11.2	9.5	0.35	0.44	0.22
0.8-1.0	C	Medium clay	Massive	7.5YR4/4	7.4	1.4	14.2	12.4	0.51	0.34	0.19
1.0-1.4	C		Sticky		7.5	2.1	19.1	15.2	0.55	0.25	0.17
1.4-1.8	C				7.6	3.1	24.0	17.2	0.45	0.21	0.17
1.8-2.0	C	Medium clay	Massive	10YR5/4	7.8	3.7	26.7	17.9	0.18	0.20	0.17

¹ EC_e = electrical conductivity in saturation paste

² ESP = exchangeable sodium percentage

³ SAR = sodium absorption ratio

⁴ TC = total carbon

⁵ TN = total nitrogen

⁶ TP = total phosphorus

Karawatha

Depth (m)	Horizon	Texture	Structure	Colour	pH (CaCl_2)	ECe (dS m^{-1})	ESP (%)	SAR ($\text{mol}_\text{c} \text{ m}^{-3}$) ^{0.5}	TC (%)	TN (g kg^{-1})	TP (g kg^{-1})
0-0.1	A1				5.3	0.6	2.3	1.3	1.66	1.34	0.32
0.1-0.2	A1	Loamy sand	Single grain	5YR 3/4	5.0	0.6	3.1	1.5	1.01	0.83	0.23
0.2-0.3	A2				4.9	0.3	3.3	1.8	0.58	0.45	0.19
0.3-0.4	A2				4.9	0.2	3.8	2.7	0.32	0.26	0.16
0.4-0.6	B2	Sandy loam	Single grain	5YR 4/6	5.2	0.1	3.7	2.0	0.20	0.20	0.15
0.6-0.8	C				5.7	0.2	4.5	2.9	0.14	0.16	0.14
0.8-1.0	C	Sandy loam	Single grain	5YR 5/6	6.1	0.5	4.7	2.9	0.17	0.13	0.13
1.0-1.4	C				6.8	0.8	4.3	3.2	0.22	0.15	0.17
1.4-1.8	C				7.0	0.8	4.2	3.8	0.24	0.13	0.18
1.8-2.0	C	Sandy loam	Single grain	7.5YR 4/4	6.9	0.4	4.0	4.8	0.06	0.10	0.16

Baxters

Depth (m)	Horizon	Texture	Structure	Colour	pH (CaCl ₂)	ECe (dS m ⁻¹)	ESP (%)	SAR (mol _c m ⁻³) ^{0.5}	TC (%)	TN (g kg ⁻¹)	TP (g kg ⁻¹)
0-0.1	A1				5.5	0.4	5.4	3.6	1.21	1.09	0.29
0.1-0.2	B1	Light clay	Granular	10YR 4/3	5.3	0.4	6.8	4.5	0.95	0.91	0.28
0.2-0.3	B2		Cracks		5.5	0.6	9.0	6.1	0.69	0.71	0.27
0.3-0.4	B2		Sticky		6.2	0.6	10.3	7.5	0.54	0.59	0.25
0.4-0.6	Bnyk				6.8	0.6	12.7	9.0	0.43	0.49	0.24
0.6-0.8	Bnyk	Medium clay	Angular blocky	10YR 4/4	7.4	1.0	16.7	10.7	0.40	0.31	0.25
0.8-1.0	Dyk				7.4	2.6	20.8	9.8	0.21	0.25	0.23
1.0-1.4	Dyk	Clay loam	Angular blocky	5Y 6/1	7.5	3.2	24.5	13.5	0.13	0.18	0.21
1.4-1.8	Dyk				7.5	3.3	22.1	11.7	0.19	0.16	0.19
1.8-2.0	C	Clay loam		5Y 6/1	7.5	ND	21.2	ND	0.14	0.14	0.22

Billinudgel

Depth (m)	Horizon	Texture	Structure	Colour	pH (CaCl ₂)	ECe (dS m ⁻¹)	ESP (%)	SAR (mol _c m ⁻³) ^{0.5}	TC (%)	TN (g kg ⁻¹)	TP (g kg ⁻¹)
0-0.1	A1				5.6	0.6	9.0	7.9	1.24	1.03	0.24
0.1-0.2	A1	Light clay	Subangular	10YR 3/2	5.3	0.6	10.9	8.7	0.95	0.85	0.21
0.2-0.3	A1		Blocky/massive		5.9	0.7	13.1	11.4	0.71	0.68	0.22
0.3-0.4	B2	Medium clay	Sticky	10YR 4/1	6.7	0.9	14.9	12.9	0.56	0.59	0.18
0.4-0.6	B2				7.3	1.3	18.3	15.1	0.48	0.47	0.17
0.6-0.8	B2	Medium clay	Lenticular	10YR 4/2	7.6	2.3	24.4	19.1	0.48	0.35	0.16
0.8-1.0	Bk		Massive		7.7	3.7	30.0	22.2	0.39	0.25	0.15
1.0-1.4	BC		Sticky		7.7	5.6	35.1	23.0	0.26	0.18	0.15
1.4-1.8	C				7.6	6.5	36.1	22.3	0.15	0.18	0.14
1.8-2.0	C	Medium clay		2.5Y 5/3	7.9	ND	42.9	ND	0.17	0.17	0.15

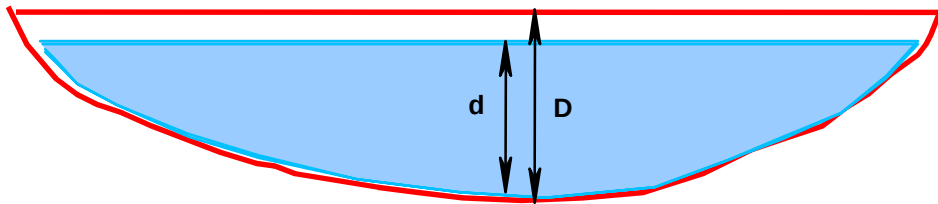
Appendix 2.1 Measurement of irrigation volumes

In this study, four methods were used to measure the total volume of water applied to each plot, and a fifth method was used to estimate infiltration of water into soil during irrigation.

Method 1. Volume stored in the furrow + flow into the soil during irrigation

$$\text{Volume of water (W)} = f (\text{Area of cross section, } d, D)$$

$$\text{Quantity (Q)} = W + \text{Infiltration}$$



Before irrigation, the geometric configuration and the cross sectional size and shape of the furrows were obtained by measuring the depths of furrows at 0, 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110 and 120 cm from the mid-point of the furrow to either side of the ridge. These measurements were repeated at various distances along the furrows and the overall mean furrow cross section and wetted perimeter were calculated.

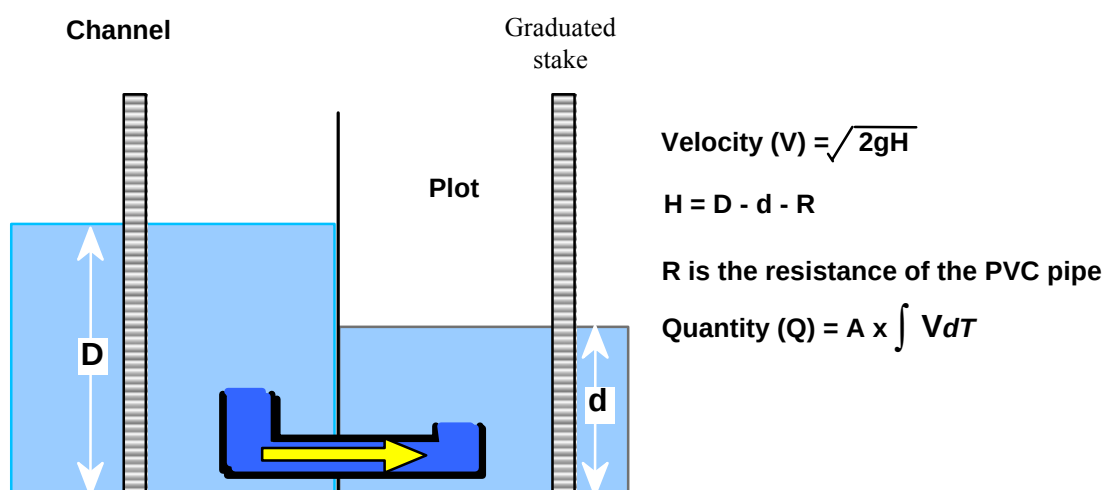
Prior to irrigation, graduated stakes were placed in the middle of the furrows at 0, 20, 40, 60, 80 and 100 m from the inlet side of the measurement plot. Immediately after irrigation, the depth of water in furrows was measured at each point along the graduated stakes.

Using these depth measurements and from the geometric configuration, total volume of standing water within these furrows was calculated. The gross volume of irrigation was calculated by including the saturated flow during the time of irrigation.

Method 2. Injection with dye

The velocity of flow was periodically monitored during irrigation by injecting dye into the stream of water entering the inlet pipe. The total volume applied was determined by multiplying the velocity of water, time of irrigation and the cross-sectional area of the inlet pipe.

Method 3. Velocity head calculation



During irrigation, the head of water at the upstream and downstream side of the irrigation channel was measured periodically using graduated stakes, one placed inside the irrigation channel and the other at the point of outlet. From this, the velocity head was obtained and the volume of flow calculated.

Method 4. Calibrated Dethridge meter

During irrigation, the rate of revolution of the Dethridge irrigation wheel was monitored at 30-minute intervals. A calibrated chart was then used to calculate the mean rate of flow of water from the measurements of revolutions and the total volume of irrigation was calculated.

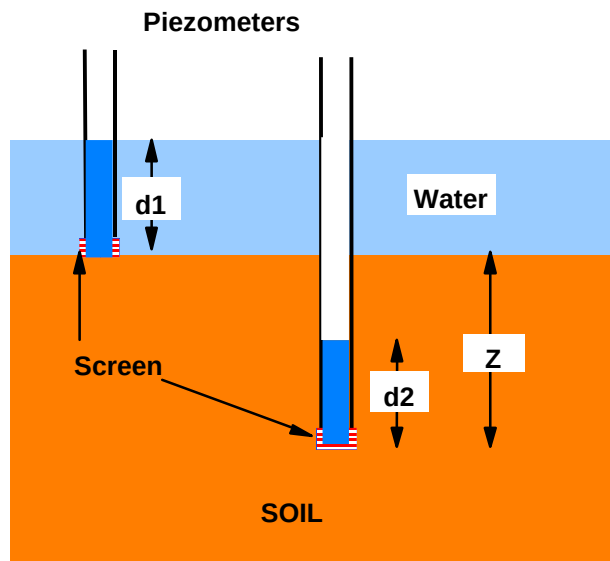
Method 5. Infiltration measurement

We estimated drainage below 3 m depth (D_i) by measuring the rate of infiltration of water into soil during irrigation and subtracting from it the total change in soil moisture storage. During irrigation, the amount of water infiltrated into soil (Q , mm) was measured using Darcy's law by installing two piezometers at the surface and at 10 cm depths in the furrows and measuring the pressure head. D_i was calculated as Q minus ΔS , where ΔS is the changes in soil water storage to 3 m depth. Run-off was calculated by difference.

Two piezometers were installed in the furrows, one at the surface and the other at 10 cm below the soil surface. During irrigation, the depth of water within these piezometers was continuously monitored using logging DATAFLOW probes to measure pressure potential and to calculate hydraulic potential ($h = p + z$, where p is pressure potential and z is gravitational potential once the soil surface is saturated). Using Darcy's law, the total flow of water into the soil (Q) was determined from the hydraulic potential gradient ($\partial h / \partial z$), saturated conductivity (K) and time duration (T) using the equation

$$Q = K \frac{h}{z} T$$

where K is estimated by a combination of a theoretical and a field method described by Libardi *et al.* (1980).



d_1 and d_2 are depths of water within the piezometers, and Z is the depth of soil.

Appendix 2.2 Measurements of soil water balance components

Net irrigation

Net irrigation (I_n) is the amount of water available to tree plantations and thus stored in the root zone depth immediately after irrigation and deep percolation. It was calculated by measuring soil moisture contents to 2 m depth before and after irrigation and adding an estimate of transpiration for those days in between the two measurements.

Evaporation of water from saturated surface soil

Under irrigated conditions, evaporation of water from soil surface (E_s) is a significant component of the irrigation water balance. E_s can be either measured (Shawcroft and Gardner 1983) or estimated (Ritchie 1972) in a number of ways. In this study, E_s was directly measured by mini-lysimeters where small isolated volumes of soil monoliths were mounted flush with the soil surface and weighed daily after irrigation to determine the rate of water loss.

E_s was measured in a total of eight mini-lysimeters installed two per plot in 'O' and 'H' treatment plots at Norwood Park. Each mini-lysimeter, 250 mm in diameter and 200 mm deep, contained an undisturbed soil monolith which had been manually extracted from the site by alternately inserting the casing and then excavating a slightly oversized column of soil. The casings were constructed from PVC irrigation pipe and the extracted monoliths were capped at the bottom. Small screened perforations in the bottom plate allowed drainage. The mini-lysimeters were then placed within the plots by excavating soil and lining with a thin PVC sleeve to hold the mini-lysimeters level with the soil surface.

The lysimeters were weighed on a daily basis for the first few days after irrigation and the schedule repeated for several irrigation events spread over different seasons. The volumetric soil moisture within mini-lysimeters was also measured periodically using Time Domain Reflectometry probes. The system was calibrated on each day of measurement (Voisey and Hobbs 1972) so that the differences between consecutive measurements were accurate to 0.1 mm ET. Details of construction and operation of the mini-lysimeters were analogous to those used by Pruitt and Angus (1960), Van Bavel and Myers (1962) and Belford (1979).

Ponded water evaporation

In plantations such as Norwood Park where soils are shallow heavy clay, the irrigation fills the furrows with water and holds it until the water infiltrates into the soil. It takes about two to three days for water to infiltrate into the soil. Evaporation of water during this period of ponding depends upon canopy cover, ponded surface area of the ponded water, and evaporative demand of the environment.

Evaporation of ponded water is difficult to measure directly and so we used certain assumptions. Based on the results of the mini-lysimeter studies, it was found that the measured maximum relative evaporation (ratio of soil evaporation to pan evaporation) of the saturated surface soils at Norwood Park was 0.6. This ratio would be higher for ponded water, but the average surface area of ponded water during the total period of ponding would be less than the total area of the plot. Hence the overall mean relative evaporation during the two to three days of ponding was considered to be equal to 0.6.

Appendix 2.3 A mini-lysimeter

Diagrammatic section of a mini-lysimeter system showing the soil monolith and casings suspended flush to the soil surface.

