



An Australian Government Initiative



Water balance and economics of irrigated eucalypts in areas with shallow saline groundwater

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

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Foreword

The establishment of tree plantations, especially *Eucalyptus* species, is used within salinity management plans as a way to control shallow saline groundwater. However, recent findings that salts accumulate in the rootzone of plants grown over shallow saline groundwater have raised uncertainty as to the sustainability of plantations.

In May 1997 a workshop was held which brought together a wide range of researchers to evaluate experimental results on processes of salt accumulation in the root zone, and advances in modelling the processes which determine the sustainability of trees planted over shallow water tables. It was acknowledged that whilst there were a number of sound modelling approaches capable of being used to analyse salt dynamics and plant growth in shallow saline groundwater environments, few were well documented, peer reviewed or widely tested. This report attempts to address some of the knowledge gaps and recommendations from that workshop, principally:

- the development of guidelines for planting trees in shallow saline groundwater areas
- the linking of biophysical models to commercial values to allow economic analyses of management recommendations
- improvement of documentation and review of models.

This report will assist landholders and advisors to judge site types and situations when there will be a positive economic return from irrigated plantations, and the period of water table drawdown. The modelling undertaken also identifies situations where irrigated plantations are not economically viable, based on establishment costs, wood production, impacts on agricultural production and estimated economic benefits.

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Executive summary

Background

The increase in land and water salinisation in southern Australia has led to an urgent need to devise and implement effective control measures. In particular, a large proportion of the land that was extensively cleared for irrigation is now underlain by shallow saline groundwater and experiencing reduced production. The establishment of tree plantations, especially *Eucalyptus* species, is increasing in popularity within salinity management plans as a way to control shallow saline groundwater. However, recent findings that salts accumulate in the rootzone of plants grown over shallow saline groundwater have raised uncertainty as to the sustainability of plantations.

A hydrological modelling exercise using APSIM was undertaken to determine the conditions under which plantations in the Riverina are sustainable and economic. The ability of APSIM to predict tree growth and salt and water balances was validated against data from a number of plantations including Kyabram and Timmering. In total, 2106 scenarios were modelled, including different plantation management, three soil types, three groundwater salinities at two depths, and four irrigation management scenarios. Throughout the report, examples are selected from the scenarios to highlight the most important processes.

An economic model was used to assess the efficacy of plantations and consisted of modules in Microsoft Excel using Visual Basic for Applications. The routines were partly derived from the FARMTREE model but were heavily modified to suit the needs of this project and new data formats available. The economic model takes biophysical data outputs from APSIM such as wood biomass, watertable depth, and irrigation water volume and salinity, converts them to variables of economic relevance, and combines them with monetary value data. It considers the benefits and costs in terms of wood production, agricultural production and river salinity, and outputs the economic results in terms of annual net benefits.

Structure of the report

Chapter 1 outlines the background, objectives, scope and intended audience of the report. This section discusses the constraints to the project and the conditions within the Riverina region so the reader can evaluate whether the manual applies to their area.

Chapter 2 is a review of the current state of knowledge on the potential groundwater control by tree plantations and the impacts of salinity.

Chapter 3 describes the hydrological modelling framework used, the assumptions made within this framework and its verification based on measured data.

Chapter 4 describes modelling the impacts of salt accumulation on plantation health under a variety of conditions and management.

Chapter 5 discusses the assumptions and results from the economic modelling used to assess the efficacy of plantations.

Summary of findings

Groundwater use by trees depends on soil hydraulic properties, groundwater salinity and depth, irrigation and plantation management. In general trees perform best with: lighter soils, deeper watertables, lower groundwater salinity, higher application of fresh water and a high-density plantation. Trees preferentially use fresh water from both surface and groundwater sources. If groundwater is saline, their use of surface water (rainfall and irrigation) increases. The sensitivity of trees to groundwater salinity decreases if they use more surface water. A general exponential form for the groundwater use by trees is suggested that describes a sharp decrease in the groundwater use from low (2 dS/m) to medium (5 dS/m) salinity and much less with higher than 5 dS/m salinities.

Trees can be effective in lowering the watertable and producing forestry products for some years. Irrigation with fresh water helps with this process as it triggers more growth and water use. However, salt accumulation in the profile over the years, causes a decrease in both water use by the trees and their subsequent capability for lowering the watertable. There seems to be a limit to the effectiveness of trees to perform as a natural sink in the shallow watertable areas, which depends on all the environmental factors (soil, climate, watertable on surrounding land, groundwater salinity) as well as management (species, irrigation, plantation management) factors. As a general guide, we would expect 6-9 effective years of growth and watertable lowering for plantations with no irrigation, increasing to 9-13 years with high rates of irrigation on light soils with good connection between shallow and deeper groundwater systems.

For the majority of the scenarios run, a negative net economic return resulted from the modelling at a 5% real discount rate. This was generally due to the high establishment costs for trees and irrigation, together with salt accumulation and poor growth with more saline water, or high costs for fresh water.

Positive net benefits were only found for a limited range of scenarios. Using irrigation with salinity at 2 or 5 dS/m, on light soils, with deep (4 m) watertables, a near optimal balance was achieved with good wood production (from MAI's in the range 20 to 35 m³/ha) and high, river salt saving (based on diversion of salt in irrigation water from river to trees). Heavy thinning of trees results in the most economic plantations, with light thinning slightly lower, and even no-thin versions still achieving positive benefits. Trees grown under the above constraints on medium textured soils were a little less economic than trees grown on light soils, but the returns were still positive.

Annuity results ranged from a maximum of \$385/ha/yr (equivalent to an internal rate of return of 8%) to a loss of \$1100/ha/yr. Not too much significance should be placed on the exact numbers output by the models, but rather on the magnitudes and relative differences.

Introduction

Background

The National Land and Water Resources Audit (2001) findings suggest that approximately 5.7 million ha of Australia's agricultural and pastoral zone have a high potential for developing dryland salinity through shallow watertables. Moreover, they predict that by 2050 as much as 17 million ha may be affected.

Salinity concerns have led to large engineering and biological scheme proposals where vegetation is growing over shallow watertables. These areas include saline floodplains and wetlands (e.g. Chowilla \$15M, lower River Murray floodplain South Australia (Sharley and Huggan, 1995)), dryland agricultural areas (e.g. Upper South East of South Australia where \$100M of benefits are expected from salt-tolerant pastures), drainage works in the Murray Darling Basin (\$10-20M/yr) and plantations for dryland salinity control in Western Australia.

Commercial farm forestry and agroforestry over shallow groundwater is likely to be an increasingly important component of catchment management. This is particularly important in regions such as the Riverina, in the Murray Darling Basin, where there are extensive areas of shallow groundwater, and concerns for salinity impacts on irrigated agriculture. Commercial tree growing on irrigated agricultural land is thought to offer an opportunity for diversified income for landholders, development of new and expanded rural processing industries, enhanced stability of rural communities, and potential land rehabilitation and sustainability benefits.

There is a concern that as plantations grow, trees will accumulate salt within the rootzone, thereby limiting their potential growth (productivity) and level of groundwater control. Site selection and management is, therefore, critical, as is acknowledgement that there may have to be some trade-offs between productivity and environmental benefits. A number of recent studies have established that similar processes operate under a range of environmental conditions but will cause different, but predictable behaviour, because of specific site and plant characteristics. These studies have shown that most of the key processes are now well understood and we should progress to the development of guidelines for managing irrigated eucalypt plantations in areas with shallow saline watertables, without needing to wait for more fundamental studies. The concern regarding salinity impacts on plantations led to a workshop sponsored by the Joint Venture Agroforestry Program on 'groundwater uptake and salt accumulation by trees over shallow watertables' in May, 1997. This provided a forum for the collation of current experimental and modelling knowledge in this field and interim guidelines for establishment of trees over shallow watertables. The workshop also identified some key areas requiring further research including best practice guidelines for plantations in a range of environmental conditions, incorporating both salinity impacts and the economics of the plantations.

There are generally two kinds of beneficiaries from commercial farm forestry and agroforestry operations over shallow watertables. Those that benefit from the wood production and those that benefit from groundwater control (including environmental benefits). Farm forestry offers an opportunity for a new long-term source of income for landholders, allowing diversification away from conventional agricultural enterprises often subject to a cost-price squeeze. There can be complementary benefits through shelter effects for adjacent crops and livestock. There are spin-off benefits to the wider regional economy as new industries are stimulated through the purchase of materials and services, and in the longer-term through the opportunities for local processing and value adding. The main expected environmental benefit is through groundwater control. This is achieved both directly from the shallow watertable or indirectly through disposal water from groundwater pumping or drainage.

The spatial extent of lowered watertable from direct groundwater use is usually limited to the area immediately under the plantation and adjacent to it (e.g. Silberstein *et al.*, 1999; George *et al.*, 1999). The actual lateral extent of drawdown out of the plantation depends on the water salinity, the depth to watertable and the soil hydraulic properties (Silberstein *et al.*, 1999). Benefits include decreased

waterlogging and salinity impacts under irrigated pastures, decreased volumes of disposal water and subsequent decreased area devoted to disposal basins, increased longevity of current irrigation areas and decreased salt loads to streams.

The clearance of native vegetation for both dryland and irrigated agriculture in southern Australia has led to widespread land and stream salinisation. The Riverina region of the Murray Darling Basin is one area that has been badly affected as watertables have risen by about 100-200 mm/yr (Ghassemi *et al.*, 1995) and now most of the irrigation areas have shallow watertables. Drainage and pumping to control groundwater levels and hence salinity are common practices in most irrigation areas. However, the cost of maintaining these schemes and problems with disposal of saline drainage waters have led to a search for additional or alternative control measures such as agroforestry or commercial plantations of fast growing tree species for timber production.

Objectives

The main objective of this project was to apply new biophysical and economic analysis to sustainability and productivity issues in areas of shallow saline watertables, for commercial irrigated eucalypt plantations for the Riverina. This work aims to inform government industry policy groups, farm forestry networks, regional plantation committees, salinity action plan groups, and other stakeholders with an interest in irrigated plantations.

The ultimate aim of the project was to determine best management for tree planting in the areas with best prospects and discourage inappropriate management for reasons of sustainability and economics.

The project addressed impediments to uptake of farm forestry and agroforestry by including an assessment of the profitability and external and environmental benefits of farm forestry, and evaluating the trade-offs between different strategies in the economic analyses. For example, use of saline water would improve the medium-term salinity benefits but could prejudice longer-term tree growth and timber returns. Close tree spacing involves high initial cost but may provide high timber volumes and early salinity benefits, so the effects of tree spacing and plantation thinning have been assessed.

The Riverina study area

The recent National Land and Water Resources Audit defined the Riverina study area based on the Interim Biogeographic Regionalisation of Australia (IBRA) (Environment Australia 2000). This report has adopted the biogeographical classification and the study area will be referred to as the Riverina Biogeographical Region or just Riverina. The Riverina covers an area of about 9 million hectares (90,000 km²), of which 77% lies in south-west New South Wales and 23% in central north Victoria. It extends north to Ivanhoe, west to Balranald and east to Narrandera in NSW and south across the River Murray to Bendigo in Victoria (Figure 1). The Murray and Murrumbidgee Rivers and their major tributaries, the Lachlan, Campaspe, Loddon and Goulburn Rivers flow westward from the Eastern Highlands across the area (hence its previous nomenclature as the Riverine Plain).

Rainfall

Rainfall across the Riverina varies from about 300 mm at Ivanhoe in the north to about 500 mm annually at Tatura in the south-east (Table 1).

Table 1: Average annual rainfall within and surrounding the Riverina.

Location	Average annual rainfall (mm)
Ivanhoe	304
Hay	366
Balranald	322
Leeton	445
Tatura	493
Kerang	410
Swan Hill	349
Albury	769
Bendigo	551

Soils

Soils are mainly shallow loams over clay. Sediments are largely fluvial, with some lacustrine and aeolian elements (Butler, 1973). The deposition of Quaternary sediments, river and aeolian, by prior streams, ancestral rivers and contemporary rivers resulted in a series of very gently sloping alluvial fans and floodplains (Butler, 1973). The soils of the Riverina are associated with the levee-floodplain features of the prior streams. The soils of the levees are red-brown earths, sandy on the crest and loamy on the backslopes. The soils of the floodplain are grey, brown and red clays.

Location of commercial plantations

The State Forests of NSW currently (in 2003) operates nine plantations with a total of approximately 200-250 ha of irrigated hardwood plantation in the Riverina. Each of these plantations is a joint venture with either private or other land management agencies. These are all (generally flood) irrigated hardwood plantations consisting of *Eucalyptus camaldulensis*, *E. grandis* and *Corymbia maculata*. Several research trials including a species trial and an oil mallee provenance trial are included in these plantations. These include: Griffith – 130 ha, Hay – 22 ha, Mulwala – 12 ha, Jerilderie – 10 ha, Tocumwal – 12 ha, Deniliquin area (3 blocks) – 36 ha.

In Victoria the Department of Natural Resources and Environment has established pilot scale commercial eucalypt plantations at 9 sites with a total area of approximately 70 ha in cooperation with landowners for evaluation of a range of irrigation strategies using saline and fresh water (Stackpole *et al.*, 1995).

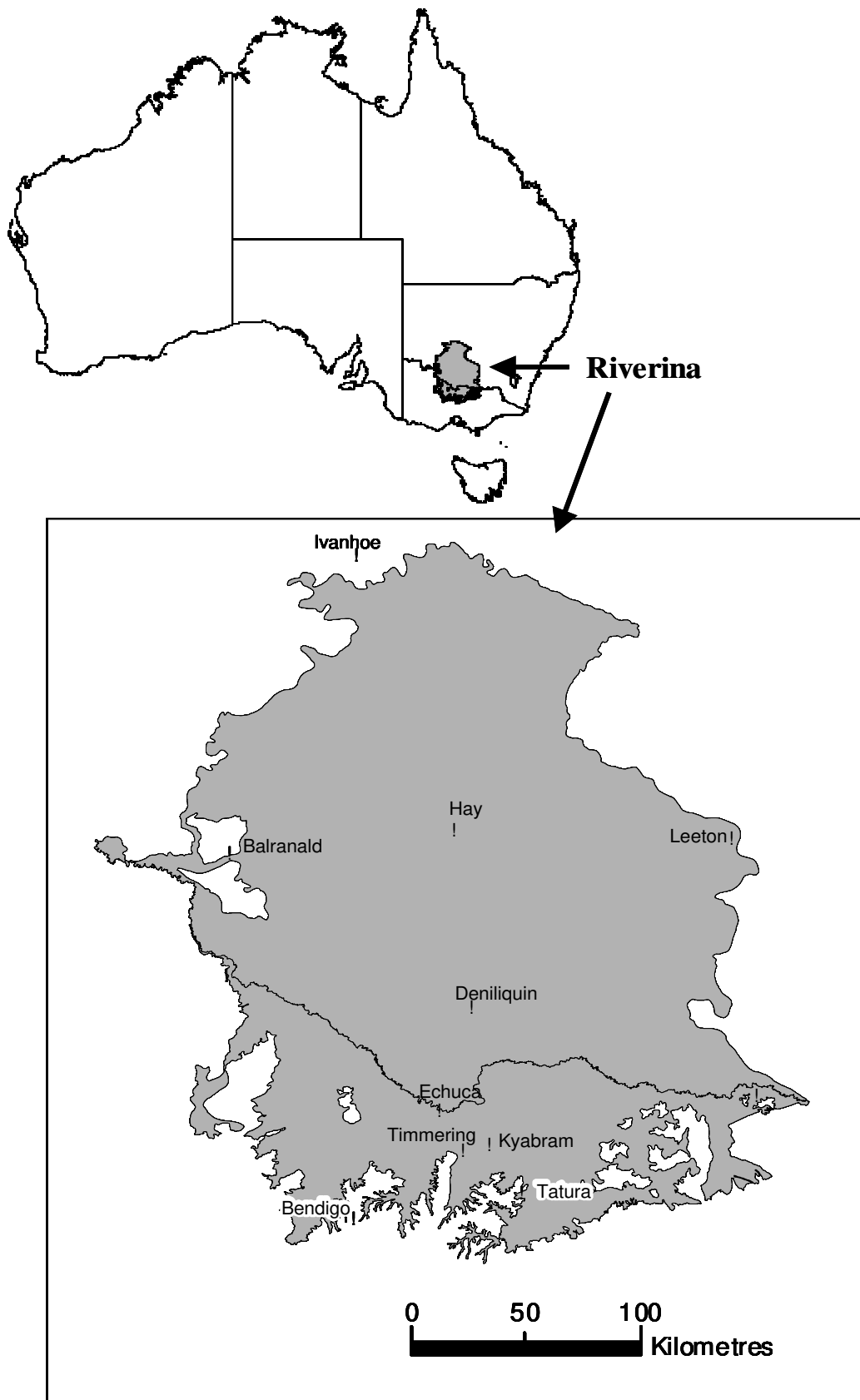


Figure 1. The Riverina study area.

Review of the potential for groundwater control by tree plantations

Using trees to control salinity

Millions of trees are being planted each year throughout the agricultural regions of Southern Australia. They are perceived as biological pumps capable of rapidly lowering watertables. Many trees are planted in the least productive parts of catchments – either rocky recharge areas in upper landscapes where there is considerable depth to the watertable or where groundwater is shallow in the lower landscape saline discharge zones. Much research has gone into the establishment of guidelines for salt tolerant vegetation species that can be grown in and around saline discharge zones. Some plant species appear capable of surviving both severe water stress and saline conditions. Many saline discharge zones have been revegetated with the most salt tolerant deep-rooted species such as saltbush and bluebush to reduce the risk of erosion and as forage for sheep (e.g. Barrett-Lennard *et al.*, 1991). However, Slavich (1992) showed that although old man saltbush (*Atriplex nummularia*) can establish and grow slowly on highly saline land its capacity to transpire saline groundwater is small relative to rainfall and irrigation. This is due to a low leaf area index induced by grazing and low stomatal conductance. Hence saltbush plantations are likely to have negligible direct impact on the groundwater hydrology of these zones.

Species that are able to maintain relatively high water consumption and growth under the severe conditions found in shallow watertable environments (e.g. alternating periods of drought, waterlogging and/or saline conditions) will have the greatest potential of adoption for groundwater control. Thus the impacts of planting tree species with some salt tolerance (e.g. *Casuarina glauca*, *Eucalyptus camaldulensis*) or waterlogging tolerance (*Eucalyptus grandis*) in these areas has been increasingly studied.

It must be noted that commercial plantations are generally not viable in areas with <600 mm annual rainfall unless groundwater or irrigation water is available (but there is research in progress by the “Australian Low Rainfall Tree Improvement Group” to select/breed species for these environments). Also, the area of plantations needed to achieve drawdown may need to be extensive. For example, George *et al.* (1999) statistically evaluated watertable drawdown below native tree plantations in 80 catchments in south-western Australia. Significant reductions in waterlevels were only observed where a considerable portion of the recharge areas of the catchment was planted. The probability of tree plantations lowering water levels in discharge areas was lower and the magnitude of the response smaller than in recharge areas. In discharge areas in south-western Australia, the maximum reduction in water level reported under native tree plantations was 2.5 m where salinity was <5000 mg/L and the groundwater system was localised (which is not the condition in the Riverina). However, the trees usually had an effect only 10-30 m from the plantation. Thus, unless special hydrological conditions existed, it was concluded that 70-80% of a catchment required replanting to substantially reduce watertables (George *et al.*, 1999). Other estimates indicate that in local catchments, planting of smaller percentages of the catchment can be effective in lowering watertables.

Achieving an acceptable groundwater balance

As plantations develop over shallow watertables, leaf area increases and roots deepen and deplete the soil water then groundwater. Thus, trees initially have potential to decrease groundwater recharge and enhance discharge through increased evapotranspiration. There are numerous reports that show water levels under trees grown over shallow watertables are lower than under surrounding dryland pastures (e.g. Heuperman *et al.*, 1984; Biddiscombe *et al.*, 1985; Engel, 1986; Bell *et al.*, 1990; George, 1990; Schofield, 1990; Bari and Schofield, 1991; George, 1991; Bari and Schofield, 1992; Morris and Collopy, 1999) or irrigated pasture (Connell *et al.*, 1998). This is assumed to imply groundwater uptake by trees.

Water use by individual trees is well correlated with growth (tree size) under a range of growing conditions (Fraser *et al.*, 1995; Hatton *et al.*, 1998; Benyon *et al.*, 1999). In addition, a positive correlation between radial stem growth and water availability, and other environmental factors, has been well-established across many of the world regions (Fritts, 1976). However, salinity control is dependent on total water use not just tree water use. Water use by other interception, soil water evaporation, and weed water use, can lead to a poor relationship between total evaporative water loss and growth on a site. Also, although volume growth rate of eucalypts is proportional to the volume of water transpired (Beadle and Turnbull, 1992), the relative proportion is site specific and depends on water availability (Honeysett *et al.*, 1992).

The effectiveness of trees in lowering saline watertables will depend on the maximum LAI (leaf area per unit ground area) reached at the site, the time taken to attain this maximum and the length of time this maximum can be sustained. Shallow watertable environments that allow for periodic relief from drought and solute accumulation will be better for tree growth. However, the planting of tree belts to manage perched watertables is of limited value unless the land slope exceeds 5 degrees (Stirzaker *et al.*, 1999). For trees to lower watertables (in environments where there is no lateral inflow of water), uptake from groundwater by plantations must exceed recharge. In some shallow watertable environments actual evapotranspiration of the plantation has been reported to sometimes exceed rainfall (Greenwood *et al.*, 1985; Greenwood *et al.*, 1992). These short-term studies suggested that although trees are primarily used to reduce recharge (Jenkin, 1981; Morris and Thompson, 1983) trees may also have potential for discharge management (Schofield *et al.*, 1989) in areas where groundwater is relatively shallow. However, when plants take up water from or near a watertable, groundwater flows towards the roots carrying salts that accumulate in the rootzone and eventually limits tree growth and groundwater use (Jolly *et al.*, 1993; Thorburn *et al.*, 1993; Barrett-Lennard and Malcolm, 1999). Studies have shown a variety of vegetation responses to changes in saline environments, raising doubts about the effectiveness of revegetation strategies for enhancing discharge from shallow watertables in the long-term (Thorburn, 1997). However, a productive tree crop may be obtained before salt accumulation has a major impact on the plantation.

Salinisation processes

Tolerance of plants to salinity

Some native tree species appear to be capable of surviving adverse conditions associated with water availability and tolerating high levels of salinity and thus have groundwater management potential. However, influencing factors need to be understood. For example, *Eucalyptus occidentalis* has high salt tolerance (EC_e 20-40 dS/m) compared with *E. camaldulensis* but the tolerance varies with genotype (Pepper and Craig, 1986; Benyon *et al.*, 1999). Also, plants are less tolerant of salinity when grown under hot, dry conditions than under cool, humid conditions (Maas, 1996). Young plants are also less tolerant of salinity than mature trees so tree establishment is also an issue.

The sensitivity of tree species to salt in soil water and the rate that trees become sensitive to salinity under reduced soil water conditions (as the watertable is lowered) is critical to the growth and water use of the tree plantation. Soil salinity (EC_e) up to 8 dS/m has only a small impact on sap velocity and hence transpiration per unit leaf area but has a big effect on reducing leaf area of *E. occidentalis* or *E. camaldulensis* (Benyon *et al.*, 1999). The presence of solutes in the rootzone generally reduces the water use of plants, initially by affecting the soil water osmotic potential which then affects the soil water potential and therefore root water potential. This in turn influences stomatal conductance and in the longer-term reduces leaf area (Munns and Termaat, 1986). Studies on native species in saline groundwater discharge areas suggest they have developed strategies to sustain their water use and growth in these environments (Slavich and Walker, 1995). These strategies include the reliance on periodic flooding that locally recharges groundwater and leaches salts from the upper rootzone.

Rate of salt accumulation in the rootzone

The rate of salt accumulation in the rootzone below tree plantations is related to the difference between transpiration and infiltration and the groundwater salinity. In some areas it may also be affected by irrigation, throughflow and groundwater inflow. Morris and Collopy (1999) showed that

average soil salinity under an unirrigated 5-8 year old plantation of *Casuarina cunninghamiana* and *Eucalyptus camaldulensis*, within a groundwater pumping area in northern Victoria, rose from 8 to 12 dS/m in 32 months. This corresponded to a chloride accumulation of more than 4 kg/m². Under an 18-year-old irrigated *Eucalyptus* plantation in a 450 mm rainfall zone of northern Victoria, watertable EC increased by 5 to 15 dS/m, relative to that under surrounding irrigated pasture over 13 years (Morris and Collopy, 1999). Feikema (2000) showed that as the watertable fell and salts accumulated in the rootzone of non-irrigated plantations at Kyabram (discussed in detail below), groundwater usage declined and thus the relative depression in groundwater level was reduced. All trees were affected by salt accumulation in the rootzone after about 20 years but the more salt sensitive species died much earlier.

Effects of salt accumulation on tree growth

Growth rates of tree plantations are determined by the characteristics of the tree species used, distribution of rainfall (and irrigation), availability of groundwater, soil depth, fertility and hydraulic properties, planting density, and fertiliser use. If salt accumulates to the point where the trees can no longer use groundwater, growth is then limited by rainfall. High transpiration, high evaporative demand and low rainfall in conjunction with declining watertable depth leads to stem shrinkage (Feikema 2000) but recovery after rainfall is often rapid. However part of the increase is due to a concurrent fall in vapour pressure deficit. Daily fluctuations in stem diameter appeared to be primarily affected by evaporation demand whereas seasonal trends are related to water availability.

Benyon *et al.* (1999) measured tree height growth of 7 year old *Eucalyptus camaldulensis* and 6 year old *E. occidentalis* on a saline discharge site in New South Wales. *E. occidentalis* had less growth reduction with increasing rootzone salinity than *E. camaldulensis*. Although soil salinity up to 8 dS/m (ECe) has only a small impact on transpiration per unit leaf area of *E. occidentalis* and *E. camaldulensis*, a 10% reduction in growth occurred in *E. camaldulensis* when the mean rootzone salinity was as low as 2 dS/m (ECe) compared with 10 dS/m for *E. occidentalis*. Similar responses occurred for stem diameter and estimated crown volume.

Morris and Collopy (1999) showed that in unirrigated 5-8 year old plantations on sites with shallow watertables in northern Victoria, *Casuarina cunninghamiana* had greater sapwood area but lower sap flux density than *E. camaldulensis* and the daily and annual water use did not vary significantly between species.

Effect of salt accumulation on transpiration

Leaf area index has been shown to be closely related to transpiration of eucalypts in water-limited environments (Hatton *et al.* 1998). Evapotranspiration of eucalypts decreases as rootzone salinity increases (van der Moezel *et al.*, 1988; George, 1991; Thorburn *et al.*, 1993; Myers *et al.*, 1998). Evidence for this is as follows:

- Benyon *et al.* (1999) showed that 7 year old *E. camaldulensis* grown on non-saline soil used more water per tree than either the *E. camaldulensis* or 6 year old *E. occidentalis* growing on moderately saline soils in a discharge zone. On moderately saline soils *E. occidentalis* had twice the area of leaves (20 m²) (and thus presumed to have used twice as much water per tree) as the older *E. camaldulensis*.
- Morris and Collopy (1999) used the heat pulse method to show water use of single trees (5-8 year old *C. cunninghamiana* and *E. camaldulensis*) grown over shallow watertables with salinity of 8 to 12 dS/m was <10 L/day in winter and over 30 L/day in summer (annual mean of 0.9-1.0 mm/day).

- Slavich (1997) showed that transpiration rates of *E. largiflorens* and *E. camaldulensis* at six sites in the Chowilla floodplain in South Australia were <1 mm/day. Transpiration rates of *E. camaldulensis* over saline (30 dS/m) groundwater were limited to 0.1 mm/day but transpiration rates of up to 2 mm/day were observed over less saline groundwater (10 dS/m). During dry periods, trees on the most saline sites relied on water from less saline zones close to the soil surface whilst trees at the less saline sites used groundwater. The maximum groundwater salinity that could be transpired by *E. largiflorens* was 40 dS/m and 30-35 dS/m for *E. camaldulensis*.
- Mensforth (1996) combined the heat pulse technique with short term measurements of transpiration at the canopy to show that *Melaleuca halmaturorum* used 0.7 to 4 mm/day (250-800 mm/yr) depending on leaf area, sapwood area, groundwater salinity and waterlogging. When groundwater salinity was high, water use was significantly below the potential evapotranspiration. Where groundwater salinity was lowest (8-14 dS/m), 1.5-3.5 mm/day of groundwater was used. Where salinity was high (63 dS/m), 0.5-2.0 mm/day of groundwater was used. Water use was least when trees were in saline and waterlogged environments.

Water sources of plantations

Water sources utilised by trees generally include rootzone water derived from rain, soil water, groundwater and surface water (and any additional applied water e.g. irrigation). There are isolated reports of active roots of some *Eucalyptus* spp. well within the saturated zone (Greenwood *et al.*, 1992) leading to suggestions that tree roots may bypass saline layers and access groundwater. However, a confining layer overlying an aquifer may prevent groundwater access to trees and restrict water uptake to perched water and that available in the unsaturated zone above the confining layer (Greenwood, 1986).

When trees are grown over shallow watertables some interaction is obviously expected. The modelling results of Morris and Collopy (1999) showed that more than half the tree water uptake (170-220 mm/year) of an unirrigated 5-8 year old plantation of *C. cunninghamiana* and *E. camaldulensis* was from groundwater with salinity of 8 to 12 dS/m. Cramer *et al.* (1999) used a combination of stable isotopes (^2H and ^{18}O) and sapflow measurements to show that groundwater was the dominant water source for *Casuarina glauca* in over 70% of sampling times at a site in southeast Queensland. However at one high rainfall site groundwater was the dominant water source for *C. glauca* in only 40% of sampling times. *E. camaldulensis* relied less on groundwater than *C. glauca*, using water from mid soil layers to a greater extent. Low water use rates were observed in both species: 1.5 to 3 mm/day by *C. glauca* and 1 to 3 mm/day by *E. camaldulensis*. Due to low water use rates, groundwater discharge rates seldom exceeded 2 mm/day with a maximum of 2.6 mm/day by *C. glauca*.

Thorburn *et al.* (1993) found that *E. camaldulensis* and *E. largiflorens* (both moderately salt tolerant) use appreciable amounts of groundwater with salinities between 10-60 dS/m on the Chowilla floodplain of South Australia. However, trees use less saline shallower water from recent rainfall or flooding in preference to groundwater when it is available (Mensforth *et al.*, 1994; Jolly and Walker, 1996). Mensforth (1996) showed that *M. halmaturorum* used groundwater from near the soil surface at the end of winter in response to groundwater rise and inundation of the soil profile. Water was then used from deeper in the soil profile over the summer in response to salt accumulation in the surface soils. Roots were most active near the soil surface after winter and near the watertable in summer (Mensforth 1996).

Feikema (2000) found that 15% of transpiration from 18-20 year old *Eucalyptus* trees at Kyabram in Victoria was from groundwater. Silberstein *et al.* (1999) found it used 25% groundwater whilst other authors suggest it is closer to 50% (Heuperman, 1999).

Groundwater discharge over time: soil water potential limiting versus salt limiting

A review by Thorburn (1996) showed a decreasing trend of groundwater uptake with increasing groundwater salinity across a diversity of field sites. Salt accumulation and low hydraulic conductivity limit the ability of the plant to use water (and hence affect growth). The rate of salt accumulation is related to the difference between transpiration and infiltration and the groundwater salinity. Stirzaker *et al.* (1999) showed that where watertables are below the rootzone (recharge zone) a wide distribution of scattered trees is required to intercept water not used by agricultural plants. If trees can access a watertable, tree belts can be spaced more than 100 m apart where hydraulic conductivity of the subsoil exceeds 5 mm/day. However, salt build-up in the capillary fringe above the watertable means that the salinity of the groundwater needs to be relatively low (less than 5 dS/m) or uptake from the watertable will be low (less than 200 mm/year). Alternatively, the rootzone must be leached of salt once or twice every ten years or there must be some exchange of salts by diffusion from a more saline capillary zone to less saline groundwater in order to mitigate the accumulation.

Intermittent leaching of solutes may allow trees to survive in otherwise marginal conditions. Mensforth (1996) showed the effect of flooding on soil salinity and consequently plant water use varied with soil type (essentially hydraulic conductivity). Transpiration rates were not appreciably reduced by extended periods of flooding (Jolly and Walker 1996) implying there was sufficient oxygen in the flood waters to maintain root function.

Case study: Kyabram field experiment

A plantation with five *Eucalyptus* species (*E. camaldulensis*, *E. grandis*, *E. globulis*, *E. botryoides* and *E. saligna*) was established under irrigation (for the first six years) at Kyabram in 1976. The watertable was 2 m below the soil surface at the time of establishment of the plantation. Connell *et al.* (2000), Heuperman (1999) and Vertessy *et al.* (2000) found that after six years the watertable was lowered by 2 to 4 m compared with adjacent irrigated pasture paddocks. However, the spatial impact was only 40 m from the plantation (due to low hydraulic conductivity of the aquifer).

After 20 years, Vertessy *et al.* (2000) modelled water use and growth of the *E. grandis* and *E. camaldulensis*. The model was parameterised so it would show the same low water use (300 mm/yr) that was observed in field measurements. Model results showed trees were heavily reliant on rainwater, deriving relatively little (15%) from mildly saline groundwater (2000-3000 mg/L) and only when evaporative demand exceeded infiltration. Feikema (2000) found that annual radial growth of the *E. grandis* did not correlate with local rainfall but this data was based on a small number of trees (virtually all the trees survived to this age, except those removed in thinning). Vertessy *et al.* (2000) concluded that non-irrigated trees, if managed properly and planted on appropriate soils, are marginal at best. If groundwater salinity is higher than acceptable to most irrigated crops, the commercial value of trees is probably limited. If the groundwater is not saline, the trees should be regarded as an irrigated crop (for economic analysis). Irrigation applied to leach salts and/or engineering approaches, such as groundwater pumps or tile drains, may be needed to sustain long-term tree growth under these conditions.

In a second plantation at Kyabram the trees reversed the hydraulic gradient after 4 years, changing it into a subsurface discharge zone (Heuperman 1999). This resulted in a build-up of salinity in the soil and groundwater (a similar gradient reversal was measured under an irrigated plantation of *E. grandis*). After 4 years, a high tree density (3 m spacing) plantation started lowering the watertable, whereas a low tree density plantation (7.3 m spaced trees) took 6 years. The deeper (10 m) piezometric pressures were not affected at any tree density. After 5 years, there was a reversal in the hydraulic gradient under the 3 m spaced trees that led to the build-up of salt within the rootzone.

Salt accumulation in the rootzone can occur under a range of soil hydraulic conductivities and groundwater salinities. Soil moisture monitoring indicates infiltration beyond 2-3 m depth at Kyabram is rare. Salt bulges form near the watertable and are associated with maximum root density. However, the depth of salt accumulation fluctuates on a seasonal basis in response to watertable levels and water extraction patterns. Salts may also be periodically leached with rainfall or irrigation. Diffusion of

salts back toward the watertable and away from high concentrations in the rootzone may also help reduce the impact on trees (Vertessy *et al.*, 2000). Morris (1997, unpublished) suggested an equilibrium peak concentration of around 15 kg/m³ (25 dS/m) would be reached within the rootzone after 20 years, with continuing groundwater uptake of 0.25 mm/day. The prognosis for the Kyabram plantation is then, sustainable, though not vigorous, as is its present condition. Leaching of accumulated salt by deep infiltration following prolonged rain, irrigation or flooding would obviously ameliorate the rootzone conditions to the benefit of the plantation, provided the event was brief enough to avoid waterlogging damage.

There is still the question of where the salt goes after equilibrium is reached (when the trees are still using groundwater) but there is no further accumulation in the rootzone? If this salt is diffusing back into the upper groundwater, it must increase there. Hence, the gradient from the groundwater to the rootzone will decrease, tending to reduce the diffusion rate and lengthen the time to equilibrium (and raise the peak concentration). The markedly higher diffusivity of salts within the fully saturated soil below the watertable should promote more rapid diffusion of these salts to greater depth. Convection, associated with diurnal and longer-term fluctuations in groundwater pressures, and lateral groundwater flow, should further assist the redistribution process. These same factors are likely to be important in the adjustment of soil conditions following the eventual harvest of the plantation. With uptake reduced to zero a relatively rapid rise of the watertable to equilibrate with the surrounding irrigated paddocks will re-dissolve the accumulated rootzone salt, and redistribution will be promoted by both diffusion and convection within the shallow groundwater (Morris 1997, unpublished).

Conclusions

Long-term studies have shown that due to salt accumulation and other effects, the net groundwater use by trees is generally less than 100 mm/yr and only up to 300 mm/yr where a shallow groundwatertable is present. With only two major exceptions, vegetation transpiration rates are much lower than potential even when water is available. The exceptions are:

- when trees are initially planted in areas where shallow rooted vegetation has been growing. The trees gradually deplete the soil water then use groundwater that, if conditions allow, causes lowering of the watertables. However, salt gradually accumulates, causing a drop in groundwater use. This is most noticeable in droughts.
- where there is a predictable seasonal leaching of salts from the soil profile through episodic events (rainfall or irrigation). However, these episodic recharge events may negate most of the discharge benefits gained during long dry spells.

The 100 mm/yr limit for net groundwater use by trees, although disappointing, is no more than can be expected from tree species that have evolved to be very conservative water users (most eucalypts). Why would such a tree use more water, especially groundwater, just because it is freely available? Profligate water users like *Eucalyptus globulus* may be better in situations where a short rotation is most suitable (Tim Ellis, pers. comm.).

Research is needed to not only study the accumulation of salt within the rootzone but also the leaching and diffusion of salt out of the rootzone by rainfall and irrigation.

Work on 'hydraulic lift' and 'reverse hydraulic lift' suggests that roots are leaky conduits that allow water to move from areas of low potential to high potential e.g. wet soil to dry soil (Dawson, 1993). One could imagine that the osmotic potential of salty soil might also add to this phenomenon, in determining the direction of leakage between soil layers (up or down) via roots, although these may be small amounts of water and not important to the water budget, but important for ecological/growth/establishment/longevity reasons. This may also have a bearing on the results from some of the more intensely studied plantations (e.g. Kyabram).

There needs to be an increased awareness of the prospect for sustainable plantations in saline areas following the establishment of an equilibrium rootzone salinity tolerable to the genotype planted. Given rainfall variability, there is a need to attach risks to this work as well. This type of research is relevant not only to the Riverina but also at the national level.

Hydrological modelling needs to examine the dynamics of rootzone salinity with recognition of the importance of diffusion and watertable movement on salt accumulation process.

There is a need to understand why there are plantations where trees are doing well, the soil is saline but not getting any more so, and some groundwater is being evaporated that otherwise would be contributing to shallow watertables and saline discharge. There is recent evidence that in some plantations, like at Kyabram, the flow of water is upward but the flow (diffusion) of salt is downward at a rate sufficient to maintain salinity levels rather than increase them. This means that even with no leaching and no watertable fluctuations, conditions in some plantations are such that the trees may be using shallow saline groundwater without the rootzone salinity increasing.

Description of APSIM and its ability to predict salt accumulation and tree growth

Introduction

The modelling framework used for this study was APSIM (Agricultural Production Systems Simulator). APSIM is a cropping system, modelling environment specially designed to allow a plug-in-pull-out approach for the integration of various simulation models. APSIM can be configured with modules suitable for the simulation of many different systems. The modules most important in this project are FOREST, MICROMET, and APSIM SWIM. These modules are a sub-set of the full configuration of APSIM, which simulates plant growth, soil water and nutrient balances as well as simulation control and management (McCown *et al.*, 1996).

SWIM (Verberg *et al.*, 1996) provides a numerical simulation of movement and uptake of water based on Richards' equation and the single-root analogue. The movement and uptake of multiple solutes is also simulated using the convection-dispersion equation. SWIM has flexible time-varying boundary conditions, which include the options necessary to simulate the inflow of water to a plantation surrounded by a high watertable provided groundwater pressures are known.

MICROMET (Snow and Huth, 1998) contains the range of calculations required to describe the energy and water balance of the interface between a vegetated landscape (plant and soil) and the atmosphere. The processes described include: interception of radiation; interception of rainfall and irrigation; modification of canopy conductance for the presence of competing canopies, humidity, and nutrition level; potential transpiration of the individual plant canopies based on the Penman-Monteith equation; and potential evaporation from the soil surface.

FOREST (Huth *et al.*, 2001) provides the capability to simulate the growth and related resource use of plantations. The key processes simulated include biomass production and partitioning, canopy development, response to and utilisation of water and nitrogen, and feedbacks to the wider carbon and nitrogen balance, such as litter fall and root turnover. The simulation of these processes has been based on prior crop modelling in APSIM and components of the 3PG (Landsberg and Waring, 1997), BIOMASS (McMurtrie *et al.*, 1990), PROMOD (Battaglia and Sands, 1997) and RESCAP (Dewar, 1997) forest models. The FOREST module also handles forest management actions such as thinning and harvesting.

The APSIM FOREST module is based on the lessons learned from the above-mentioned crop and forest productivity models. A range of APSIM modules provide daily data for meteorological conditions and uptake of water and nitrogen and so that time step is used for all growth calculations. Growth is calculated as,

$$\Delta G = R_{\text{int}} \text{ LUE } \min(F_t, F_n, F_{\text{vpd}}) F_w$$

Where ΔG is daily growth, R_{int} is daily intercepted solar radiation (MJ/m^2), LUE is the light use efficiency (g/MJ) and F_t , F_n , F_{vpd} and F_w are growth modifiers for temperature, nitrogen, vapour pressure deficit and soil water supply respectively. R_{int} is calculated using crown cover, leaf area, and an assumption of exponential light extinction.

Tree water demand is calculated using the MICROMET module which is developed from the work of Snow *et al.* (1999) and Kelliher *et al.* (1995), while tree water uptake is calculated using SWIM soil water modules available in APSIM.

Daily growth is partitioned to leaf, stem, bark, branch, taproot, and roots using specified partitioning rules which vary with tree size and water or nitrogen stress. Leaf area growth is calculated from daily leaf biomass growth and an age-dependant specific leaf area. Similarly, root length calculations utilise a specific root length, with root length partitioned spatially according to supplies and demands for both water and nitrogen. All biomass pools can undergo senescence and detachment. Simple first-order

decay rates can be specified and these are modified according to daily growth potential to capture annual variation in litter fall rates. Nitrogen taken up from the soil mineral pools is partitioned to individual plant parts according to sink strengths calculated from nitrogen deficits in each plant part. Nitrogen in the biomass detaching from the living plant is returned to the soil or surface fresh organic matter pools depending on the source of the material.

Solute movement within and out of the soil profile are calculated in SWIM using the Advection-Dispersion equation, which will provide information for the fluxes of salt within the profile. The solute concentration in the water flowing across the bottom boundary in either direction is dependant on the direction of water flow. Thus:

- if the water flow is downward, solutes will progress down across the deepest node. Once solute has passed the node it cannot return to the profile. Bulges may move across this node, but as we calculate convection only for this node the concentration gradient, or shape of the bulge, is not considered at this node
- if the water flow is upward then it is assumed that the solute concentration in the water entering the profile is the same as the specified groundwater concentration. This will act as a supply of solute into the profile.

Salt impacts on tree growth in many ways (Kozlowski, 1997) but for the purposes of these simulations it was assumed that the primary effect of rising salinity would be through osmotic effects on plant water use. The osmotic potential of the soil salt solution is calculated in SWIM as the product of the solute concentration in the soil water solution and an osmotic coefficient. The value of this parameter was chosen such that a salt solution with an electric conductivity of 20 dS/m would exert an osmotic potential of 15 bar. As a result, build up of salt to such levels would render water in the soil unavailable to roots as the osmotic potential is of the same order of magnitude as the minimum plant xylem potential. As a result, plant water use and growth would decrease as salt builds up to these levels.

A simplified approach to waterlogging has been taken in the modelling component of this project. Rather than try to mechanistically model processes such as oxygen diffusion, we have assumed that air-filled pore space is a good indicator of root health under wet conditions.

SWIM utilises a single-root analogue in the calculation of root water uptake. In the following simulations it is assumed that anaerobic conditions would reduce the effective root length density of a portion of soil. The level of such an anaerobic condition is related to the air-filled pore space below the saturated water content of the soil. If the difference between the volumetric soil water content and the saturated volumetric water content is greater than 6% then no effect of roots is said to exist. As water content increases above this level, the effective root length density is discounted until 3% below saturation at which point roots are said to be totally ineffective.

The result of these assumptions is that uptake of water from the watertable can only take place at the top of the capillary fringe. The level to which a tree can depress the watertable will depend on the ability of the tree to remove water from that capillary fringe and the rate at which the watertable can respond to this loss. The shape of the capillary fringe (which is dependant upon soil hydraulic properties) will also affect how close to the watertable the roots will be able to operate. Roots will access water closer to a watertable with a shallow capillary fringe rather than deep capillary fringe.

Lower boundary condition and watertable beneath pasture outside the plantation

As plantation productivity is strongly affected by the accumulation of salt within the rootzone, it is essential that the amount of water and salt flowing into and out of the rootzone be simulated reliably. The effect of the plantation on the watertable depth outside the plantation is also important as this influences the economics of the plantation (see Economic modelling). The distance outwards from the plantation edge that experiences lowered watertables in response to the plantation water use, S , is calculated using one of several candidate drainage equations (see below). The drainage equation will also supply the shape of the watertable outwards into the pasture from the plantation edge. The

information required to apply the steady-state drainage equations is the simulated current watertable depth within the plantation, the assumed watertable depth below the pasture at sufficient distance from the plantation (that it is unaffected by the plantation), assumed net recharge from the pasture, and the effective hydraulic conductivity (Appendix 1).

Net inflow of groundwater into the plantation rootzone can be considered as the total of lateral and vertical flow. The lateral flow component is sourced locally from the recharge of the surrounding land (usually pasture). The vertical flux component comes from the aquifer underneath the plantation.

Several drainage equations have been examined for their suitability to approximate the lateral inflow and the rise in watertable depth away from the plantation. Of the several single-layer steady-state equations (eg. Luthin, 1978), the Hooghoudt method was selected for further examination because of its simplicity and wide use. The important assumptions employed in the development of the Hooghoudt method are:

- water flow is at steady state
- there is an underlying impermeable layer at some depth
- above the impermeable layer the soil's hydraulic properties are uniform, and
- the Dupuit-Forchheimer flow assumptions are appropriate.

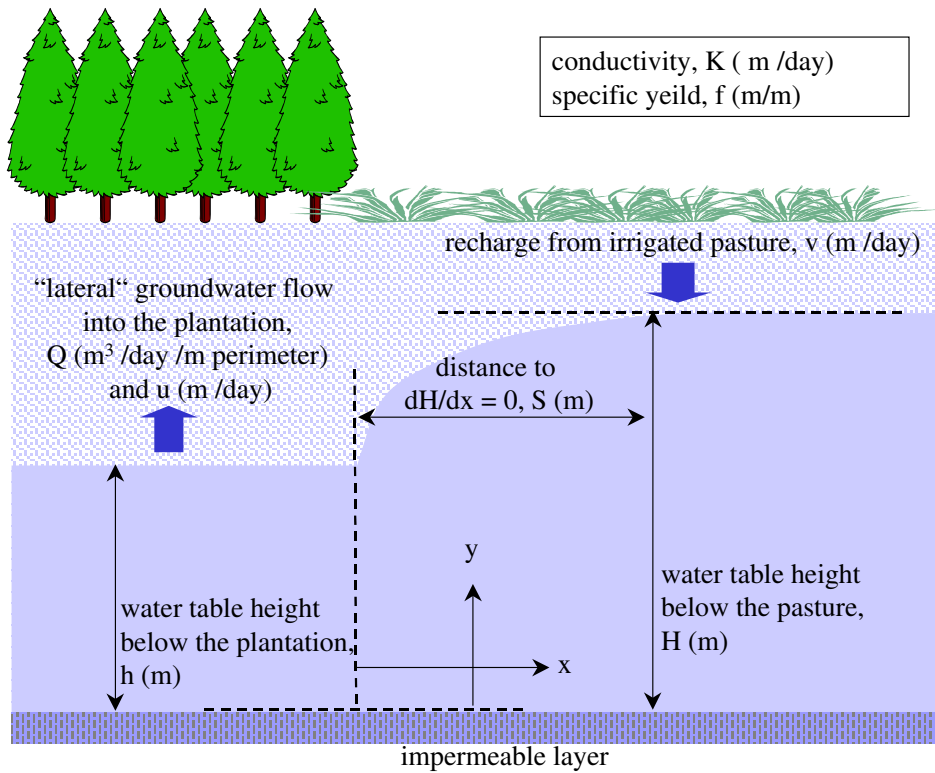


Figure 2. Definition of symbols used in the drainage equations.

For our purposes, the Hooghoudt equation is utilised by first calculating the distance out from the plantation that the watertable is drawn down, then the shape of the watertable beneath the pasture is calculated from Equation 1: (see Figure 2 for definition of the variables used in Equation 1):

$$S = \sqrt{\frac{K(H^2 - h^2)}{v}} ; \quad y = \sqrt{\frac{(2Sx - x^2)v}{K} + h^2}$$

Equation 1

Vertical flux is considered to be linearly dependent on the head difference between the watertable under the plantation and outside the plantation. The total flux is specified at the bottom boundary of APSIM as a gradient using Darcy's equation. Applying this boundary condition, the model can predict the position of the watertable in the plantation at each time step (daily).

Background to the application of APSIM to data from Kyabram

APSIM was applied to existing data from the Kyabram plantation, an experimental site of 2.4 ha planted to a range of eucalypt species and surrounded by pasture (Connell *et al.*, 2000; Heuperman, 1999; Silberstein *et al.*, 1999, Vertessy *et al.*, 2000). The plantation was established in 1976 to give information on tree growth and effect of plantation on watertable drawdown. The plantation was irrigated for the first 6 years only. In 1982 a network of piezometers was installed in and around the plantation to monitor the watertable position. Groundwater salinity under the plantation was reported in the range of 2000-3000 mg/L (Heuperman, 1995 and Silberstein *et al.*, 1999). Annual stem growth was estimated from the data of Baker (2002, unpublished). Water use, profile salinity, and Leaf Area Index (LAI) data were available for a two-year period of intensive measurements (Vertessy *et al.*, 2000).

Site description and measurements of tree growth, water use, watertable depth, and salinity are given in Vertessy *et al.* (2000) and Feikema (1995). The principal inputs and parameters required to drive the modelling are the soil hydraulic properties, meteorological data, and tree growth and water use parameters. For soil moisture retention, measured data for Lemnos loam soil (K.A. Olsson, ISIA, Tatura, unpublished data) were used (see Appendix 1). Saturated hydraulic conductivity of soil under the plantation was obtained from measurements on the site (Feikema 1995, Vertessy *et al.* 2000) and the required meteorological data were mainly from Kyabram Research station provided by Silberstein *et al.* (1999). Climate data over 22 years (starting in 1977) included, daily values of rain, maximum and minimum temperature, radiation, and atmospheric vapour pressure. The parameters required to drive FOREST for the example below were determined from simulations of *Eucalyptus grandis* for effluent irrigated conditions at Wagga Wagga, NSW (Snow *et al.*, 1999a and b) and published results of water and nitrogen responses from Gympie, Qld (Cromer *et al.*, 1993) and long term growth data from Coffs Harbour, NSW (Birk and Turner, 1992). For example, a LUE of 1.3 g biomass/MJ (total shortwave radiation) has been used. This is fairly consistent with values for other C₃ plants including data for *Eucalyptus grandis* (Cromer *et al.*, 1993). Specific leaf area was specified to be age dependant with a reduction from 16000 mm²/g to 8000 mm²/g by six years of age (Cromer *et al.*, 1993; Myers *et al.*, 1996). Leaf turnover was calculated assuming leaf longevity of approximately one year (as assumed by Cromer *et al.*, 1993; and Specht and Specht, 1989) and shown in simulations of the data of Myers *et al.*, (1996). Partitioning of biomass between plant parts was fitted to the data of the range of experiments described above.

Comparison of APSIM predictions with field observations at Kyabram

The APSIM simulations were run for 22 years (from 1977 to 1999) and key results, stem volume, watertable predictions and chloride profiles are shown in Figure 3 to Figure 5. These results demonstrated the ability of APSIM to simulate the main outputs of importance to this project.

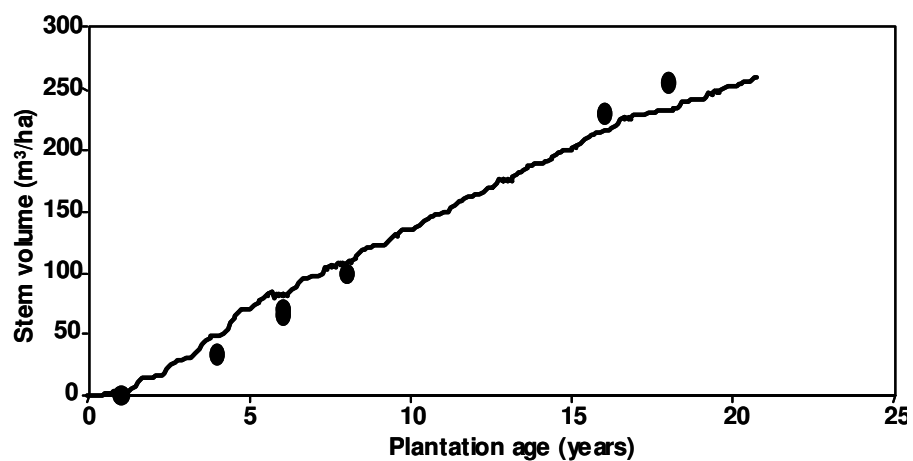


Figure 3. Measured (points) and simulated (line) stem volume of *Eucalyptus grandis* with plantation age at Kyabram.

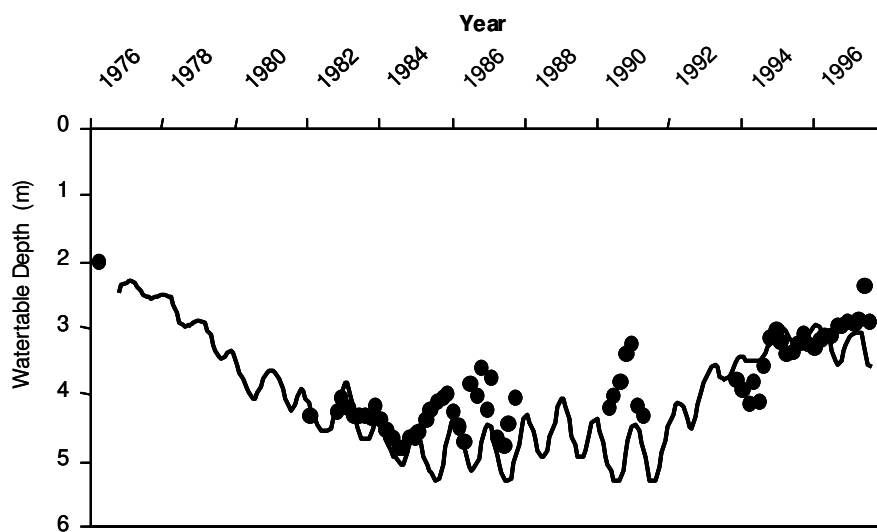


Figure 4. Measured (points) and simulated (line) watertable depth at Kyabram.

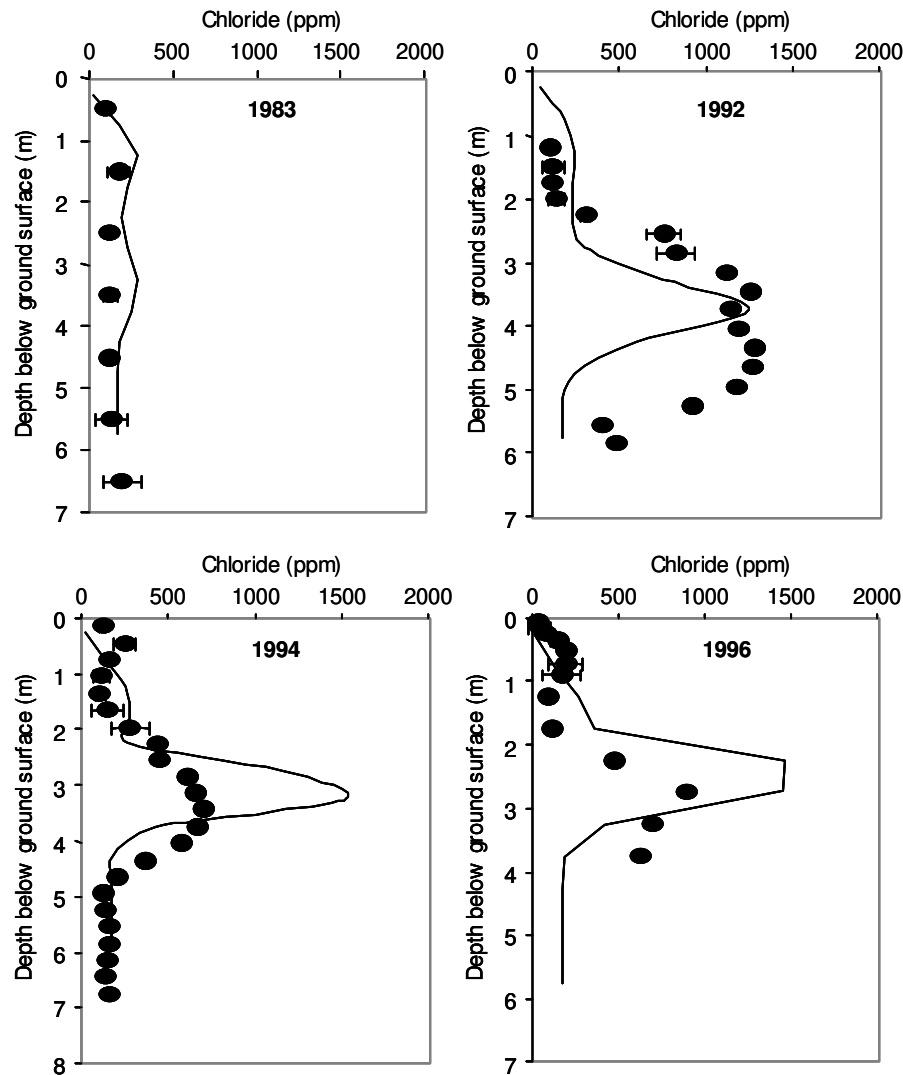


Figure 5. Measured (points) and simulated (line) Chloride profiles in 1983, 1992, 1994 and 1996 at Kyabram.

Application of APSIM to data from Timmering

Further testing of the simulation framework was undertaken using data for the “Trees For Profit” (TFP) trial site at Timmering (Stackpole *et al.* 1995). The experimental design of the Timmering site included the response of a range of eucalypt species to irrigation with fresh or saline (c. 6 dS/m) water. In this case only the data for *Eucalyptus grandis* has been used. Measurements at this site include tree growth, salt accumulation and watertable depths and were available for the first six years of the plantation. Analysis of the field data suggested that variation in watertable depth at the site was principally governed by regional groundwater levels. As such, this site could not be used to test the lateral flow modelling framework developed to simulate the hydrological conditions which occur at the Kyabram experimental site. It was therefore decided to specify these groundwater fluctuations and to use the Timmering dataset for testing other components of the APSIM modelling framework, such as the salt balance and tree growth sub-models. Observed planting densities and irrigation volumes were used in the model to specify plantation management and initial salt profiles were set to be similar to the results obtained when the plantation was at two years of age.

Comparison of APSIM predictions with field observations at Timmering

Figure 6 to Figure 8 show comparisons between observed and predicted values of salt accumulation, and growth of *Eucalyptus grandis* at Timmering site. The simulated (lines) agreed reasonably well with the observed (points) values for the Timmering site.

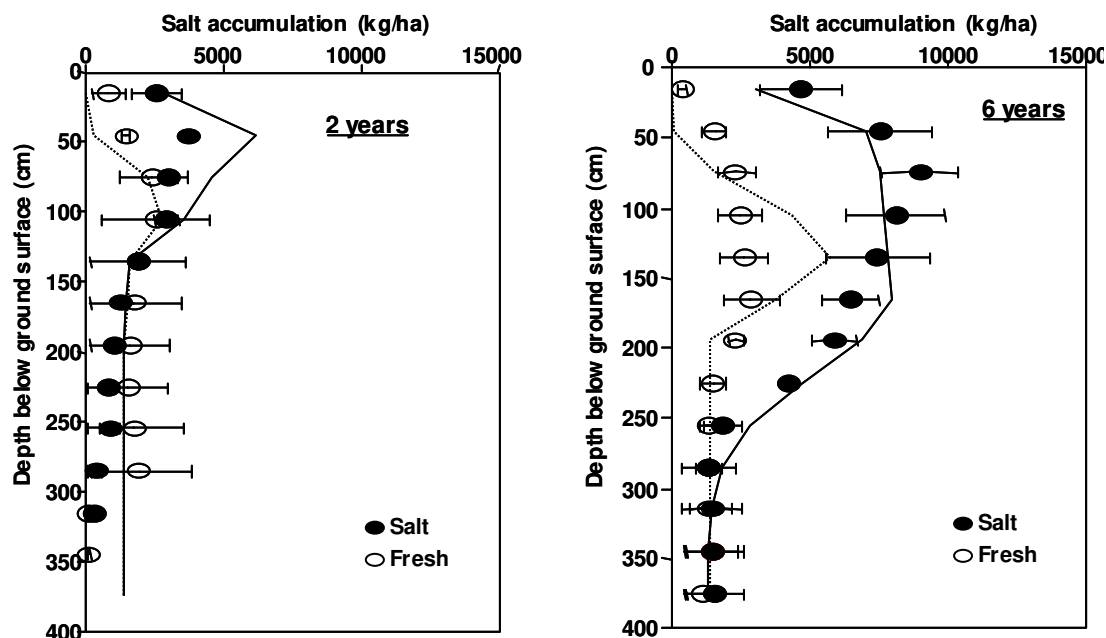


Figure 6. Salt profiles for fresh and saline irrigation water treatments at age two and six years for *Eucalyptus grandis* at Timmering TFP trial site, simulated (lines) and observed (points).

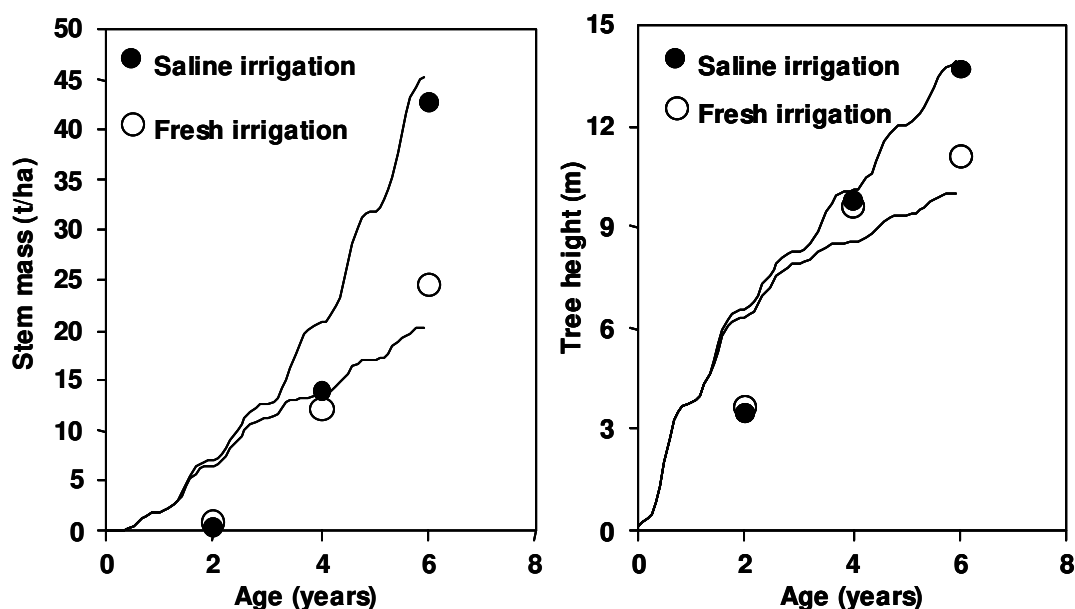


Figure 7. Stem mass and tree height for fresh and saline irrigation water treatments to age six years for *Eucalyptus grandis* at Timmering TFP trial site, simulated (lines) and observed (points).

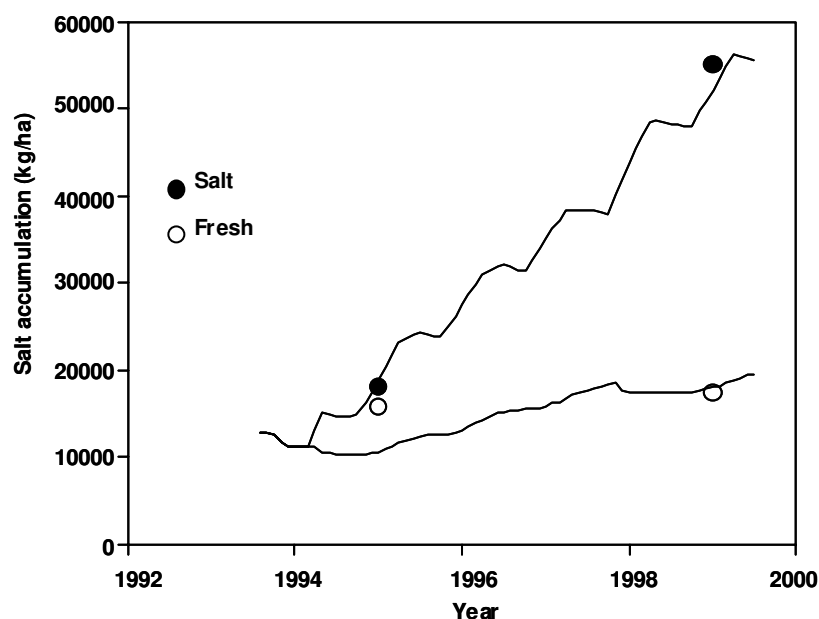


Figure 8. Total profile salt accumulation for fresh and saline irrigation water treatments to age six years for *Eucalyptus grandis* at Timmering TFP trial site, simulated (lines) and observed (points).

Comparison of APSIM and 3PG simulations

Comparison of outputs from 3PG (Landsberg and Waring 1997) were thought a valuable check in identifying problems in parameterisation or operation of APSIM. 3PG's simple rootzone model and static watertable assumptions make it unsuitable for predicting the hydrological impacts of plantations using groundwater. However, it provided a rapid and convenient means of evaluating the relative growth of plantations subject to different site conditions and management strategies including saline irrigation.

A range of soil type, watertable depth and groundwater salinity combinations for *Eucalyptus grandis* at Tatura, (planted at 4 x 2 m spacing with 50% thinning, and irrigated at 1000 mm/yr with 2 dS/m water) were compared. The APSIM and 3PG outputs were very similar for 4 m watertables, especially on lighter soils (Figure 9). With 2 m watertables APSIM's growth predictions were much lower than 3PG's, which were similar to the predictions for 4 m watertables (Figure 10). The differences were greatest in heavy soils. In heavy soils with 2 m watertables APSIM predicted that the plantations never became well established and were dead by age 13 years. Heavy soils and watertables at 2 m depth are typical of many parts of the Riverina, and with irrigation of 1000 mm of 2 dS/m water it is expected that growth would be similar to that predicted by 3PG rather than that by APSIM. The reasons for the difference between APSIM and 3PG predictions include the groundwater dynamics that are set in APSIM.

When selecting plantations in heavy soil with shallow, 2 m, watertables, APSIM is simulating a sluggish aquifer – a soil system that becomes easily waterlogged if supply volume (rainfall and irrigation) is too high.

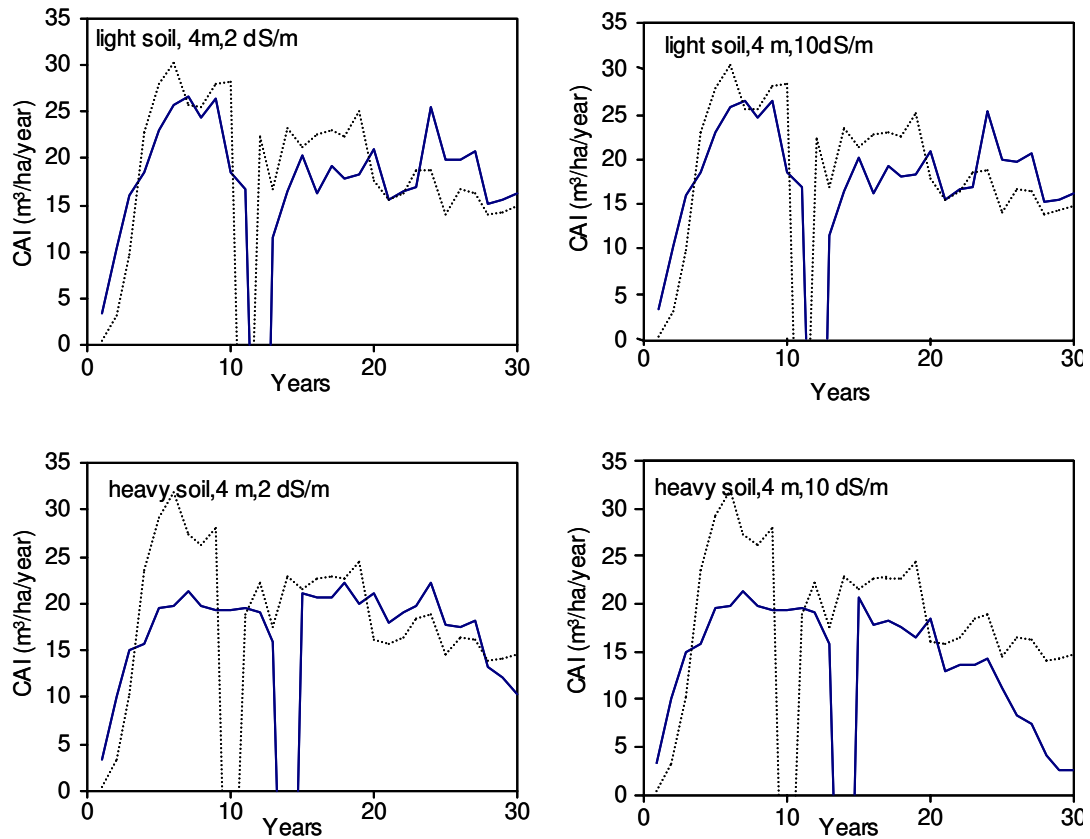


Figure 9. Growth predictions of APSIM (solid line) 3PG (dotted line) for two soils and groundwater salinities, with watertable at 4 m, for *Eucalyptus grandis* at Tatura, planted at 4 x 2 m spacing with 50% thinning, and irrigated to 1000 mm/year with 2 dS/m water [Note: The sudden drop in CAI around age 12 is due to thinning].

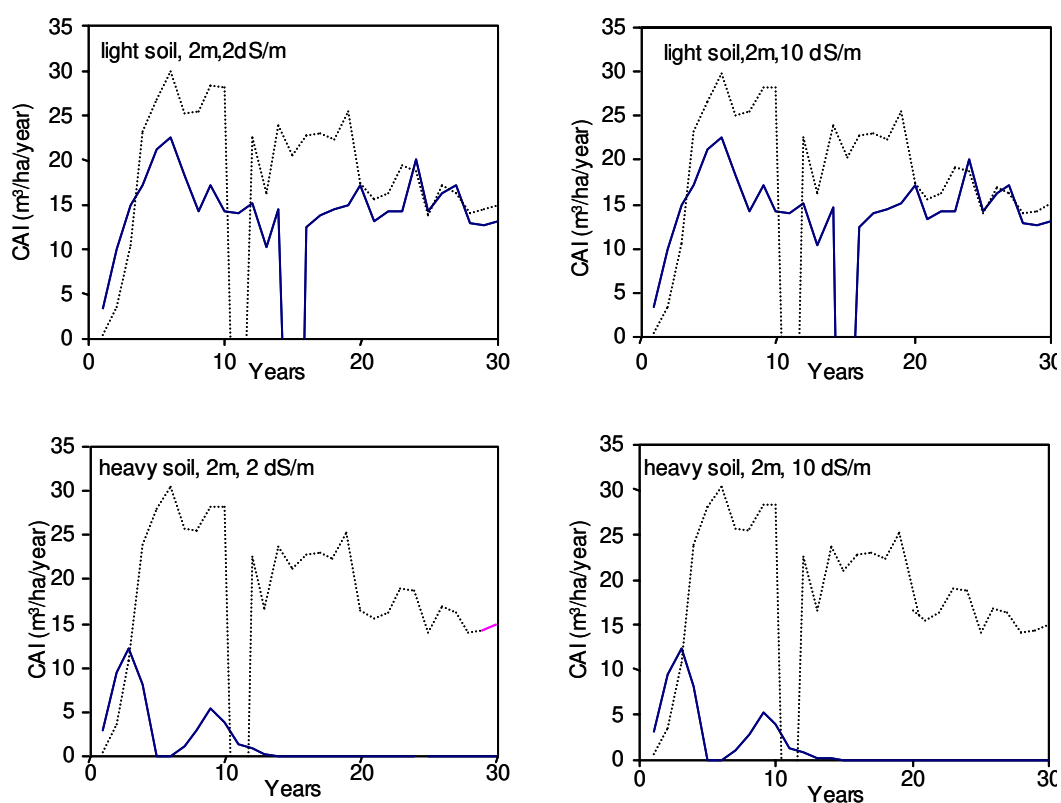


Figure 10. Growth predictions of APSIM (solid line) and 3PG (dotted line) for two soils and groundwatersalinities, with watertable at 2 m, for *Eucalyptus grandis* at Tatura, planted at 4 x 2 m spacing with 50% thinning, and irrigated to 1000 mm/year with 2 dS/m water [Note: The sudden drop in CAI around age 12 is due to thinning].

Modelling tree growth and salt accumulation impacts using APSIM

Modelling scenarios

APSIM was used to simulate a range of scenarios which covered various combinations of climate, soils, groundwater salinities and depths, irrigation and plantation management across the Riverina. Appendix 2 shows how annual rainfall, the seasonal distribution of rainfall, solar radiation, maximum temperature, vapour pressure deficit (VPD) and pan evaporation vary throughout this region in January. (Note that the town locations provide context only – the surfaces were generated from more than 500 meteorological stations).

As there is relatively little climatic variability throughout the region (see also Appendix 3) and keeping in mind that the project was primarily interested in irrigated plantations (meaning that management will partially mitigate the effects of climate variability), climate information from only 3 locations – Tatura, Leeton, and Kerang (Figure 11) was used. Factors considered in the scenario modelling are summarised in Table 2.

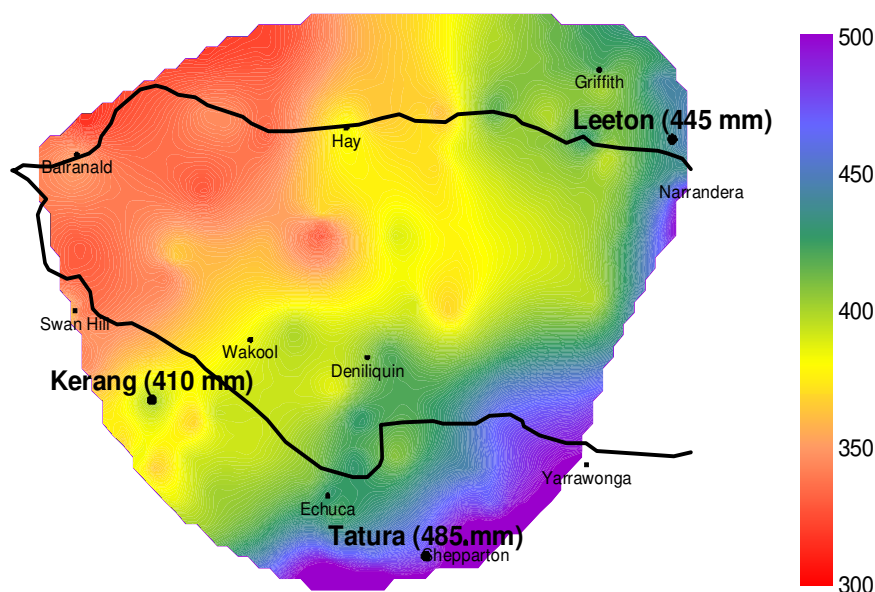


Figure 11. Annual Rainfall variation (mm) across the Riverina.

Climatic data from 1970 to 1999 were obtained for the three locations from the Patched-point Meteorological Data (Queensland Department of Natural Resources, 1999). The Patched-point Dataset contains daily rainfall, minimum and maximum temperatures, radiation, evaporation and vapour pressure. The dataset combines original Bureau of Meteorology measurements for a particular meteorological station with infilling of any gaps in the record using interpolation methods.

Table 2: Modelling scenarios.

Parameter	#	Options
Climate	3	• Tatura • Leeton • Kerang
Soil type	3	• Light • Medium • Heavy
Groundwater salinity	3	• 2 dS /m • 5 dS /m • 10 dS /m
Irrigation water salinity	4	• 0.2 dS /m • 2 dS /m • 5 dS /m • 10 dS /m
Species	1	• <i>Eucalyptus grandis</i>
Irrigation management	4	• No irrigation • 6 x 50-mm irrigations during summer • 20 x 50-mm irrigations during summer • “smart” irrigation based on dynamic scheduling
Watertable depth	2	• 2 m, with seasonal fluctuations • 4 m, with seasonal fluctuations
Spacing-thinning	3	• Planted at 625 /ha (4 x 4 m), no thinning. • Planted 1,250 /ha (4 x 2 m), smallest 50% (resulting in 625 /ha) harvested for pulp/poles at a specified DBH . • Planted 1,250 /ha, smallest 80% (resulting in 250 /ha) harvested for pulp/poles at a specified DBH.

A sandy loam topsoil to 0.25 m depth was assumed to occur throughout the Riverina and used in all simulations. A smooth transition (a gradual linear change in parameters rather than an abrupt change) was assumed to one of three subsoil types, light, medium, or heavy textured soil, at a depth of 0.4 m. Soil physical properties for the medium soil were taken from Geeves *et al.* (1995). Soil physical properties needed for the modelling of the lighter and heavier textured soils were constructed around the medium soil. The subsoils were assumed to have uniform structural and physical properties with depth. The soil hydraulic properties were set using a single-component smoothed Brooks-Corey equation. Various reports and soil maps (e.g. ASRIS soil property maps) were consulted for estimating soil hydraulic properties throughout the Riverina. Appendix 4 gives a summary of soil hydraulic properties used in the simulations.

Three initial groundwater salinities (EC), 2 dS/m (low salinity), 5 dS/m (medium salinity), or 10 dS/m (high salinity) were considered in the modelling, along with watertable depths of 2 m (shallow) and 4 m (deep). As discussed previously, the combination of shallow watertables and heavy soil texture results in waterlogged soils under some irrigation conditions.

Four irrigation management options were covered in the simulations (all irrigation rates are NET irrigation):

- **no irrigation** – (0 mm/yr)
- **low irrigation** (300 mm/yr) – 6 irrigations of 50 mm between October, 1 and March, 31 (i.e. approximately monthly), except:
 - in the first 5 years if the watertable was within 0.50 m of the surface then no irrigation was applied

- from 5 to 30 years no irrigation was applied if the tree LAI was less than 0.15 or the watertable depth was within 1 m of the soil surface
- **high irrigation** (1000 mm/yr) – 20 irrigations of 50 mm between October, 1 and March, 31 (i.e. approximately every 10 days) with the same exceptions as listed above
- **smart (scheduled) irrigation** – the irrigation season was set to between October, 1 and March, 31. During that time the soil water storage in the top 1 m was assessed and irrigation was applied if this available water was less than 75% of the maximum plant available water storage capacity. In addition, three times during the summer the total amount of salt in the soil water in the top 2 m of soil was assessed. If that amount exceeded 40 t/ha then additional irrigation (with the same salinity as the usual irrigation) was applied in an attempt to leach the salt. The amount applied was calculated as that required to fill the top two meters of soil to field capacity plus a further 200 mm. The same exceptions as listed above applied to both the scheduled irrigation and the leaching.

Each of the above irrigation regimes was applied with four different water salinities:

- 0.2 dS/m (fresh)
- 2 dS/m (low)
- 5 dS/m (medium)
- 10 dS/m (high).

For example, an irrigation management of low_med indicates a low amount (300 mm) of irrigation water with a medium salinity level of 5 dS/m. Only one tree species was simulated, *Eucalyptus grandis*. Plantation management was:

- **no thinning:** trees were planted at 625 stems/ha and the assumed initial Leaf Area Index (LAI) was 0.025
- **light thinning:** trees were planted at 1250 stems/ha and the initial LAI was 0.05. When the average stem mass exceeded 116 kg the number of stems was reduced by 50% and the amount of biomass was reduced by 28% (this assumed that the smallest stems were removed in the thinning). The corresponding reduction in biomass was estimated from data on diameter distributions using a Weibull function (Morris, pers.comm.)
- **heavy thinning:** trees were planted at 1250 stems/ha and the initial LAI was 0.05. When the average stem mass exceeded 231 kg, the number of stems was reduced by 80% and the amount of biomass was reduced by 56%.

Two components of groundwater inflow to the plantation from surrounding pasture were considered:

- **vertical flow** for the light soil was set so the amount of inflow was sufficiently high that most of the uptake of groundwater was matched by inflow (so the rate of drop in the watertable was slowest in the lightest soil). In the heavy soil the rate of inflow was considerably less than the amount of groundwater use, so that, relative to the amount of water used, the watertable dropped more rapidly in the heavy soil than the light soil. The medium soil was set between the two extremes
- **lateral inflow** to the plantation from the surrounding pasture was calculated using the Hooghoudt drainage equation with the following values and assumptions:
 - The lateral hydraulic conductivity was assumed to be 2.5 times the vertical conductivity (which was set by the subsoil conductivity; Appendix 4)
 - The recharge rate in the pasture outside the plantation was assumed to be 100 mm/yr evenly spread throughout the year.

The plantation dimensions were 300 x 300 m. This combination of factors produced a total of 2106 scenario model runs, which were reported in three output files and stored in three databases – one for each location.

Results of scenario modelling

To analyse the impact of each factor in the model simulations, results at one site (Tatura) and one tree species (*Eucalyptus grandis*) were studied in detail. This was followed by an analysis of processes at two other locations (Leeton and Kerang). Comparisons were then made across all sites to determine generic rules about the interaction of processes affecting the growth of *E. grandis*.

Tatura predictions

In these results, wood biomass refers to total above-ground woody biomass which includes bark and branches. The steady increase in wood biomass production is an indication of growth. When the cumulative curve of biomass starts to level off it shows that tree growth has ceased due to waterlogging and/or salt accumulation in the soil profile. Although the growth stops when this occurs, the trees may not die but can survive for a while with a low leaf area and water use.

The impacts of groundwater salinity

Groundwater salinity was the major factor affecting the growth and survival of the trees. The impacts of groundwater salinity can be seen on wood biomass, salt accumulation in the rootzone, leaf area and tree water use.

Figure 12 shows a comparison of wood biomass production of *E. grandis* with three levels of groundwater salinity of irrigated trees on a light textured soil (with no plantation thinning) and a 2 m watertable. The impact of salinity was not seen for 9 to 15 years, depending on the groundwater salinity. The production is halved where the groundwater is highly saline (10 dS/m). Salt accumulation to the whole depth of the profile over a 30-year period reached 179 tonnes/ha where groundwater salinity was 2 dS/m and 267 tonnes/ha where groundwater salinity was 10 dS/m. The accumulation of salt in the soil profile would cause a decline in tree growth and productivity in all cases.

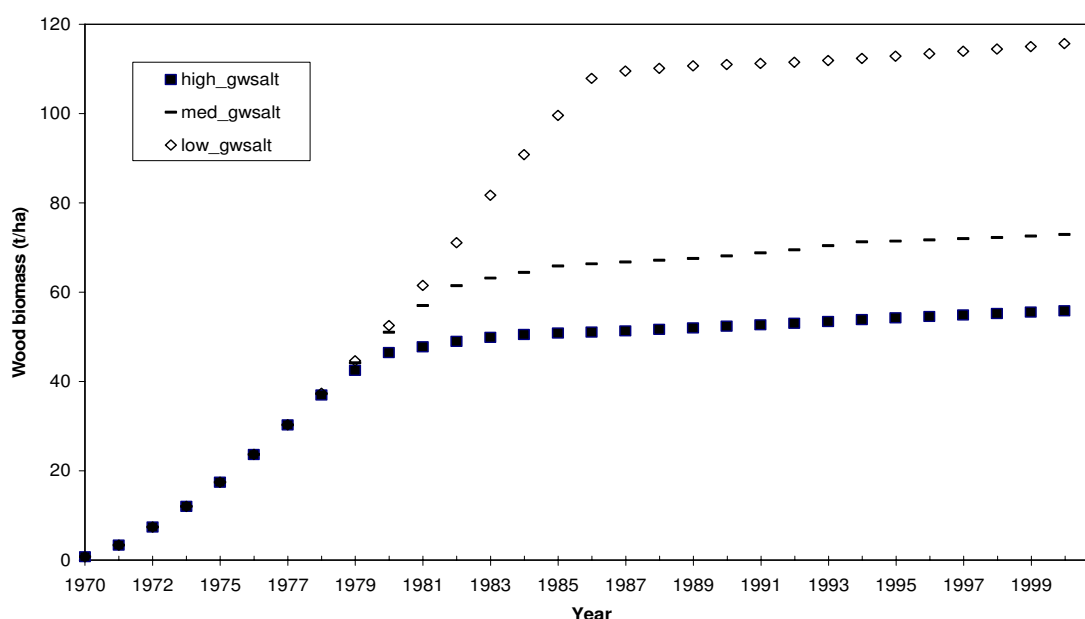


Figure 12. Wood biomass production of *Eucalyptus grandis* on a light soil, with low irrigation of low salinity (2 dS/m) at Tatura, deep watertable.

The LAI (Figure 13) and tree water use (Figure 14) predictions for trees grown where the groundwater salinity is high and low show the same trend. Where groundwater salinity is high the trees reach maximum growth, LAI of 1.4, and a maximum water use of about 400 mm/yr, after about 8 years. Trees growing on the same soil, with lower groundwater EC (2 dS/m) will continue to grow for another 5 years and reach an LAI of 2 before any decline in growth becomes apparent as a result of salt build-up in the rootzone. These data demonstrated a lower growth rate than observed in saline

water irrigated plantations of *E. grandis* at Kyabram, Timmering and other Trees for Profit pilot plantations.

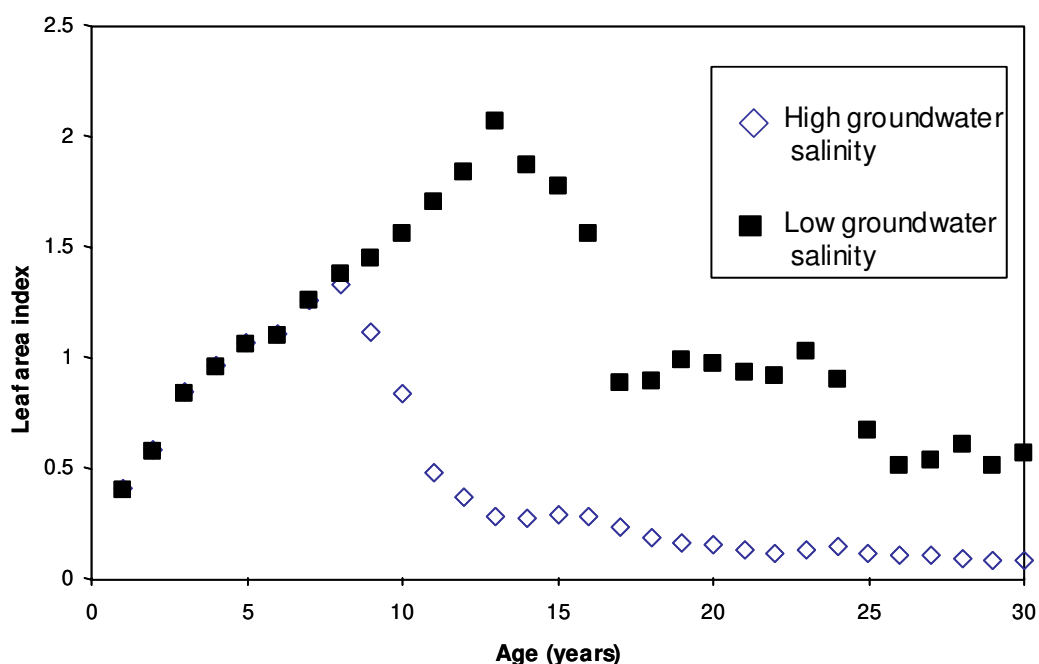


Figure 13. Leaf Area Index predictions for *Eucalyptus grandis* on a light soil, low irrigation with low salinity (2 dS/m) in Tatura.

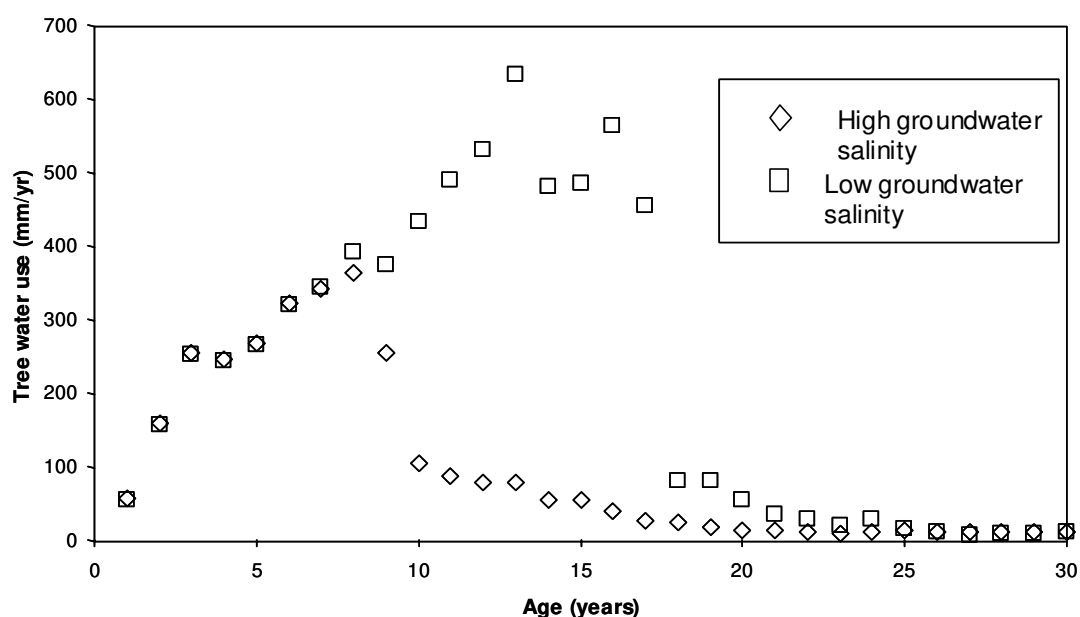


Figure 14. Tree water use predictions for *Eucalyptus grandis* on a light soil, low irrigation with low salinity (2 dS/m) at Tatura.

The impact of planting density

Figure 15 compares thinning with low irrigation volumes with low salinity, with prediction of wood biomass (a) and watertable position (b). With the low density option (625 trees/ha, spacing of 4 m x 4 m) the lowering of the watertable lags behind the treatments with higher initial densities (tree spacing of 4 m x 2 m). The latter also lower the watertable about 0.5 m deeper than the lower density

(no thinning) plantations. This is expected as, in the case of high density plantations, more trees per area of plantation would be using groundwater resulting in a lowering of the watertable under the plantation. These examples may not show the effect of thinning (only initial stocking density) since the biomass is so low that they may not have achieved required threshold size for thinning.

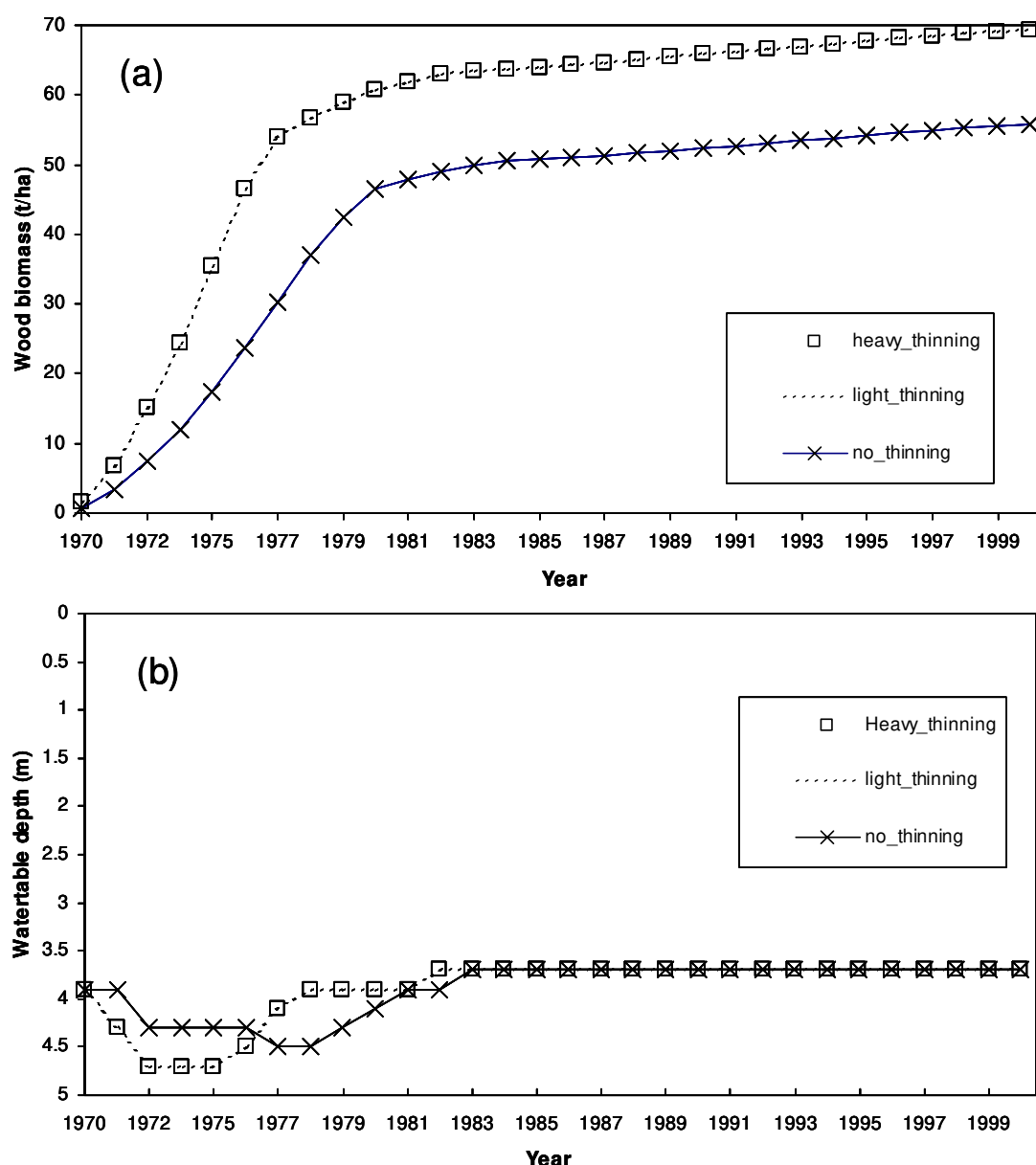


Figure 15. Effect of thinning on production (a) and watertable predictions (b) for *Eucalyptus grandis* on a light soil, low irrigation with low salinity (2 dS/m), Tatura.

Depth to watertable

The effect on watertable depth under the pasture is shown in Figure 16 (a). As long as the watertable below the pasture surrounding the plantings is of low quality, its depth in the profile is not an important factor due to limited groundwater use. When groundwater is of a better quality (lower EC), and groundwater use by the trees is considerable, then the position of the watertable is important as long as it is within the reach of the trees, but not too shallow to make them waterlogged.

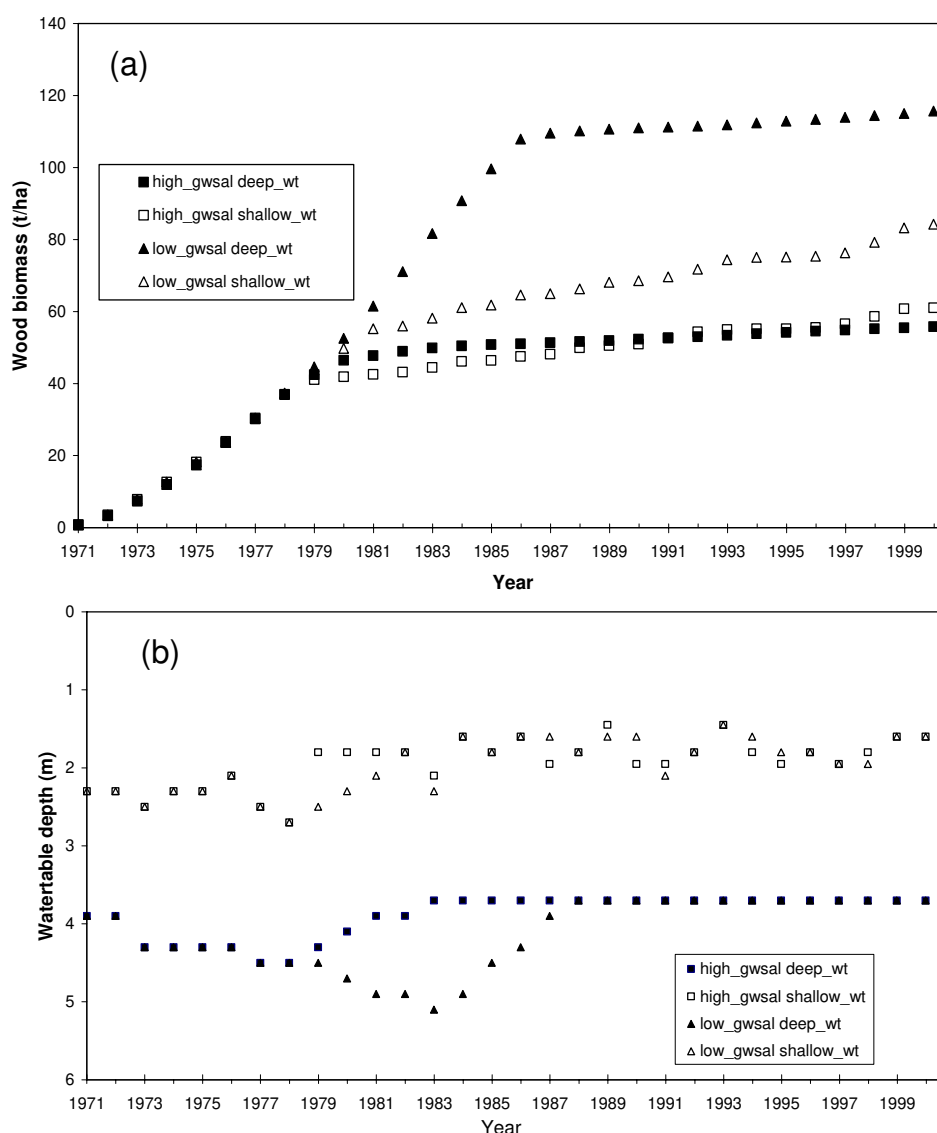


Figure 16. Effect of watertable depth below the pasture on tree production (a) and plantation watertable (b), Tatura, *Eucalyptus grandis*, light soil, low irrigation rate and salinity.

Predictions of watertable depth and plantation production in Figure 16, suggest that groundwater salinity has more impact on tree growth than watertable depth when irrigation is limited. Tree production differs greatly at comparable depths to watertable depending on the groundwater salinity level, such that watertable depth becomes more important with decreasing groundwater salinity. In the shallow watertable scenario the trees are affected by waterlogging, so that they don't perform as well as when the watertable is deeper. When the groundwater salinity is high, tree response is affected by salts regardless of the depth to watertable, indicating less groundwater use from a more saline watertable. [Note: In the Economics section watertable depth was more important than groundwater salinity for the higher irrigation options. By comparison, scenarios reported in this chapter are low irrigation /low growth ones and unlikely to be economic].

Groundwater and irrigation water use by trees

Trees use groundwater as a supplement to the available surface water (irrigation or rain). As shown above, salinity of the groundwater plays an important role in the uptake of groundwater by the trees. If the groundwater salinity is low, trees will use groundwater in preference to more saline surface water. Trees grow better if the groundwater salinity is low and fresh surface water is supplied, so they can utilise both sources of available water.

Figure 17 shows that in a saline environment caused by saline (10 dS/m) groundwater a high amount of irrigation (1,000 mm/yr) is needed before a substantial increase in production occurs. A low irrigation rate of 300 mm/year will not be adequate for leaching of the salts in the profile. Note that low application of irrigation will result in a yield similar to not irrigating at all. One important conclusion from this analysis is that in order to provide a more suitable environment for tree growth when the groundwater is more saline, a high application of water (1000 mm/year or more) is needed, provided that watertable rise as a consequence can be controlled by natural or artificial (drainage or pumping) means.

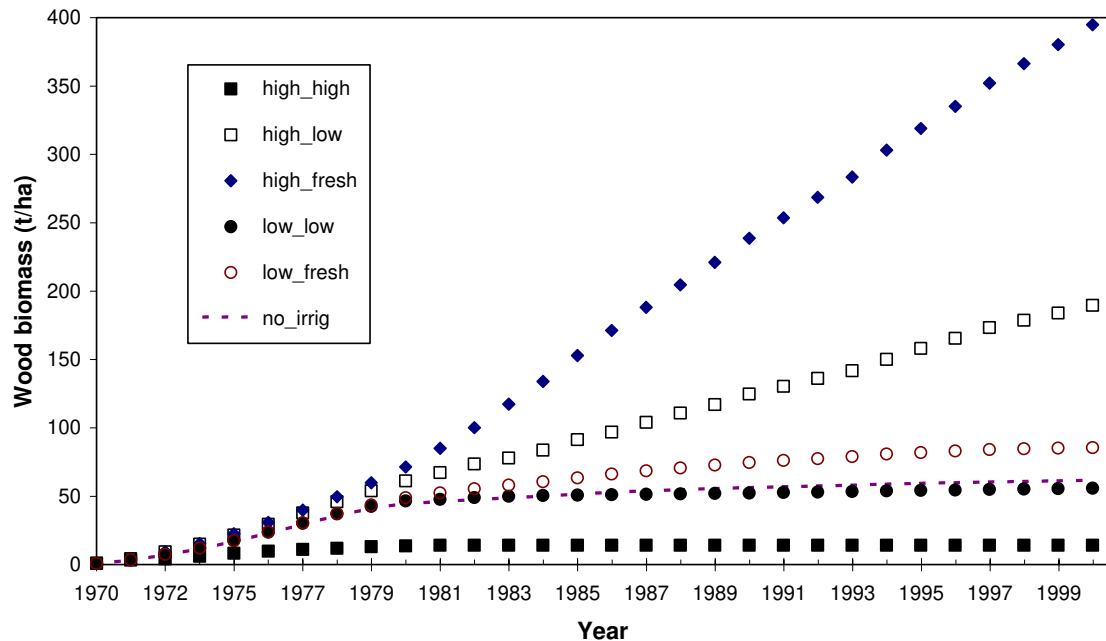


Figure 17. Wood biomass production of *Eucalyptus grandis* on a light soil, 4 m watertable depth, EC 10dS/m at Tatura.

The relationship between irrigation amount and production is further explored in Figure 18, which shows that increasing the amount of irrigation will, in most cases, increase the production, except when the irrigation water salinity is high (10 dS/m) which actually decreases the growth because of salt build-up in the profile. The positive growth response is greater for fresher water and it is more pronounced at irrigation rates higher than 300 mm per year. This confirms the earlier observation that only higher application of irrigation would make a substantial difference in increasing the tree production when groundwater salinity is high.

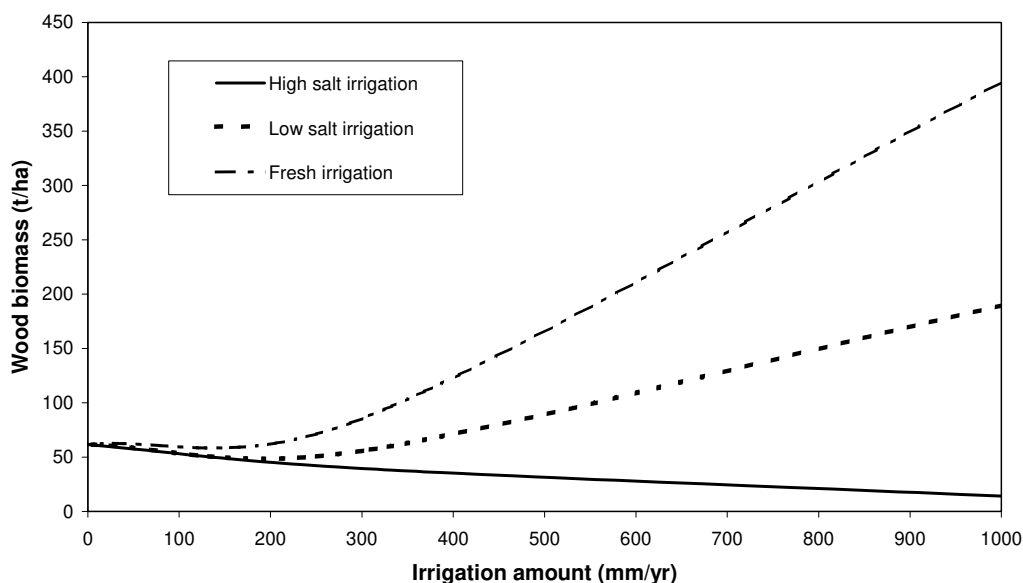


Figure 18. Relationship between irrigation amount and salinity with tree production (after 30 years) in a medium soil in Tatura (watertable at 2 m depth and salinity of 10 dS/m).

The quantity of groundwater used by trees depends on watertable position with respect to the roots, the hydraulic properties of the soil, and salinity of the groundwater and as such, depends very much on the dynamics of the system. Figure 19 shows just one of the possible relationships between the groundwater use of *E. grandis*, at Tatura, at the age of 15 years, with no irrigation. Groundwater use is considered as the inflow to the plantation, or the amount of groundwater used by the trees. Different relationships are obtained with other combinations of irrigation management, spacing and species. In general, trees will use more water when planted in light soils with less saline groundwater, than if planted in clays with more saline groundwater. There is a sharper decrease in the use of groundwater as salinity increases from 2 to 5 dS/m than beyond 5 dS/m and the decrease is more observed in the medium and light soil than in clay, which does not show much sensitivity to the groundwater salinity.

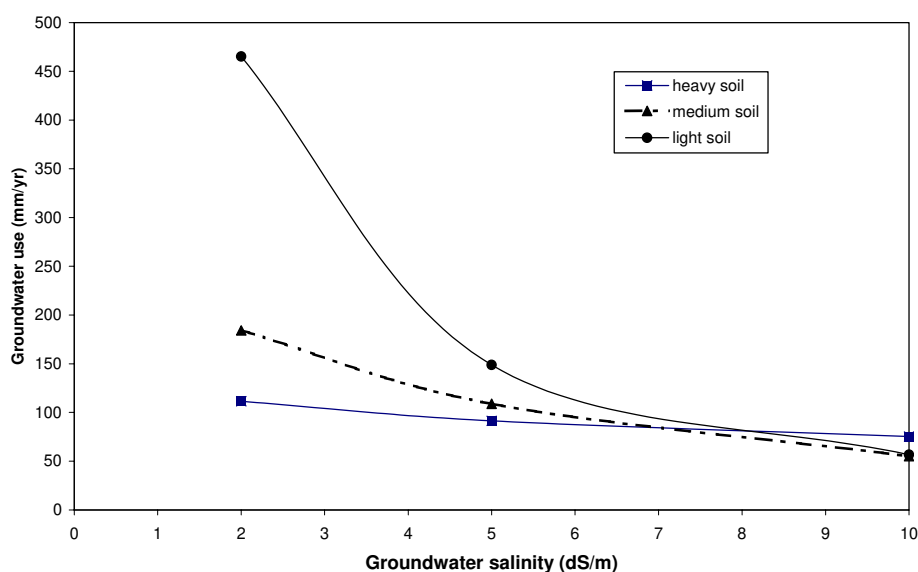


Figure 19. Relationship between groundwater use and salinity for a *Eucalyptus grandis* plantation (no_irrigation, watertable at 4m depth) in Tatura (only three points shown).

If fresh water is applied using scheduled irrigation the amount of groundwater uptake by the trees declines for all soils indicating less use of groundwater when more surface water is available. The relationship with the groundwater salinity would be a flatter curve than in a no_irrigation condition.

Analysis of our results showed that in most cases the relationship between groundwater use of trees and groundwater salinity (EC in dS/m) could be described by an exponential function (Eq^n (2):

$$Eq^n (2): GWuse = A * EXP (-B * EC)$$

In which GWuse is in mm/year; A & B are parameters depending on the soil, watertable depth (m), and age of the trees (yrs). The above relationship describes the nature of the sharp reduction of the groundwater use when groundwater salinity increases up to about 5 dS/m. An example for the A & B values found for the low irrigation regime at the age of 15 years (with $R^2 > 0.96$) are given in Table 3.

Table 3: Parameters of Eqn (2) for a 15 yr old *Eucalyptus grandis* plantation with low irrigation and 4 m watertable depth at Tatura.

Soil type	A	B
Light	672.8	0.256
Medium	240.7	0.149
Heavy	120.1	0.048

It should be noted that the distinction between different soils includes the effect of vertical inflow, which is related to the soil type in these simulations. For a light soil, vertical inflow is not a limiting factor and it will replenish the groundwater used by trees at a relatively fast rate. This should be taken into account when comparing results for different soils all throughout this modelling exercise.

The exponential function suggested for tree water use with groundwater salinity is similar (in the functional form) to the generalised relationship suggested by Stirzaker (2002) based on some experimental data (Thorburn, 1996) with values resembling a light soil property according to the above table.

Comparison of *Eucalyptus grandis* results in all locations

In a no_irrigation scenario, trees respond in a similar way and the groundwater salinity level is a factor in determining the yield. Hence, regardless of the location, trees at all sites with high groundwater salinity (10 dS/m) only produce up to 80 tonnes/ha at age 30 yrs. For the low groundwater salinity, the tree productions are higher, but still close in all locations. Tatura produced less than the other two sites, which is probably the result of higher rainfall (up to 18% more on the mean annual basis) and lower demand. This causes a shallower watertable (Figure 20b), which interacts with tree growth and production (Figure 20a).

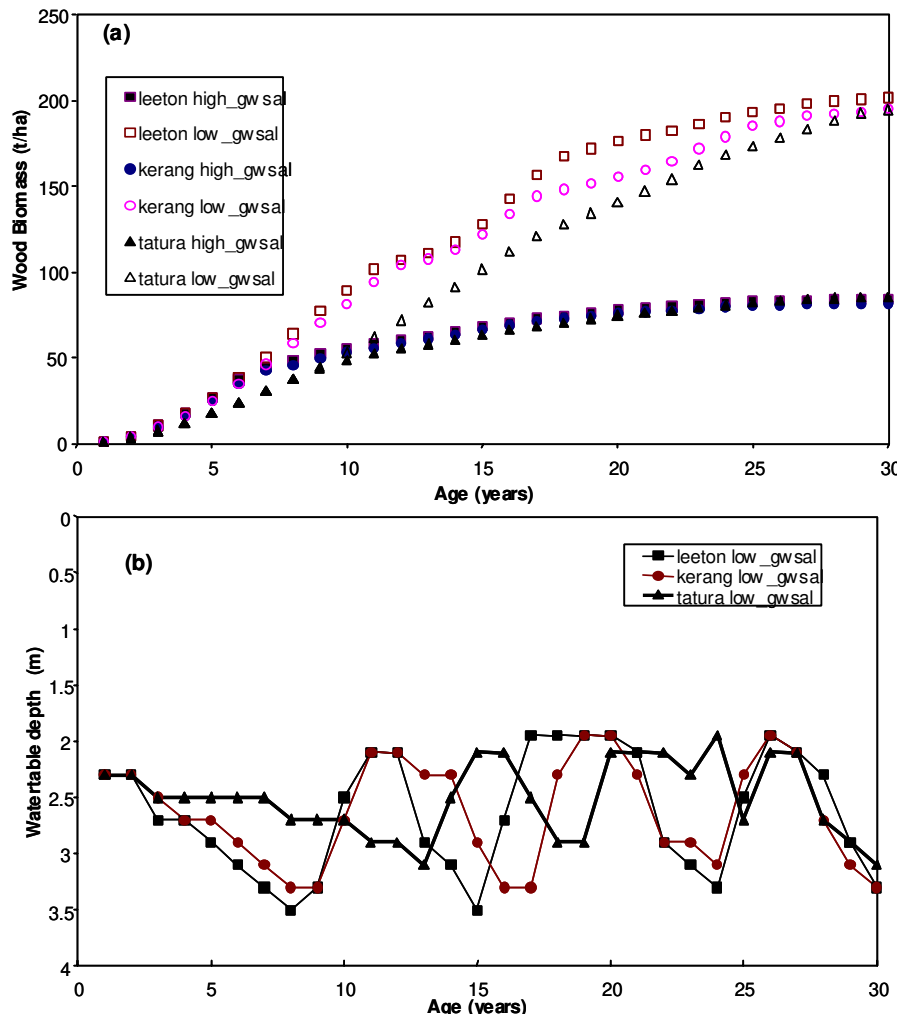


Figure 20. Wood production and watertable predictions for *Eucalyptus grandis* on a light soil at all sites.

At all sites trees perform better on lighter soils than heavy soils. Yield is generally greater on lighter soils with low groundwater salinity. The lower hydraulic conductivity of the heavy soil, causes less inflow of water into the plantation from the surrounding land and the underlying aquifer, making less water available for tree use on these soils and hence there is less tree growth and production.

When there is greater use of surface water by trees the sensitivity to the groundwater salinity decreases. In particular, with the scheduled irrigation of fresh water the performance of all treatments come close to each other and they produce a much higher yield, irrespective of the soils (Figure 21). Heavy soils have the potential for greater growth and production if enough fresh surface water is available (as in scheduled irrigation). This can be seen at all sites.

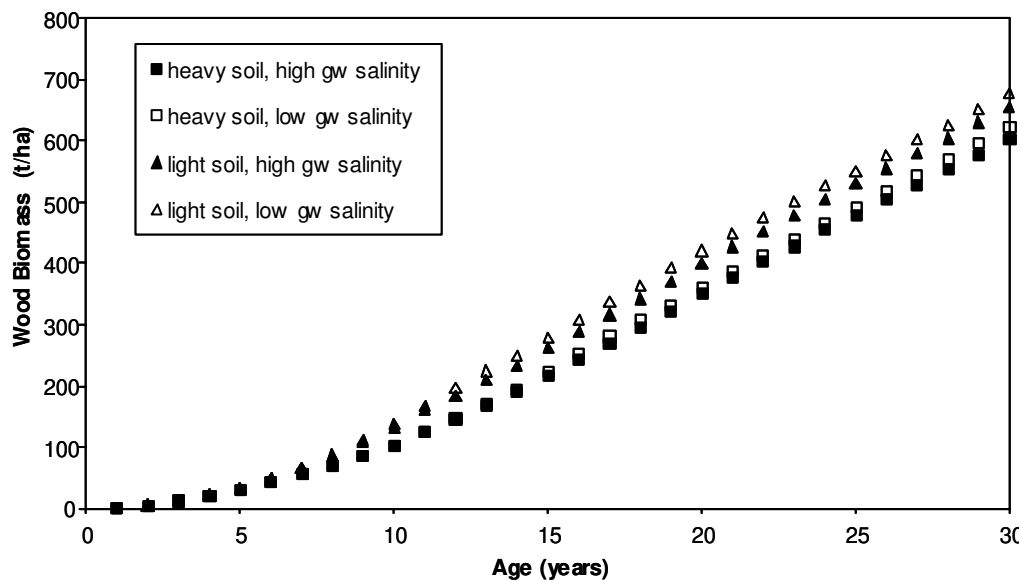


Figure 21. Production of *Eucalyptus. grandis* at Leeton, on a range of soils with watertable at 4m depth, with scheduled irrigation of fresh water.

Application of high rates of irrigation with fresh water will increase tree production and growth in all locations, and on all soils, except where the watertable under the pasture is high (2 m depth). In the latter case, high application of irrigation water needs to be with fresh water to avoid the detrimental effects of salts and the shallow watertable in the profile. Thus, if the watertable is shallow, only high application (1000 mm) of fresh water would improve the trees environment for better growth and survival. In all soils with a deep watertable a high application of low salinity (2 dS/m) irrigation water would leach some salt out and make some improvements to tree growth relative to the no-irrigation option. High rates of application of highly saline water would have detrimental effects soon after planting.

The effect of irrigation amount and salinity can be observed by plotting wood production with increasing salinity of the irrigation water for each irrigation amount (high or low). For example, Figure 22 shows a decreasing trend of wood production with increasing salinity of the irrigation water on a light soil with low groundwater salinity (2 dS/m) for the Kerang site. This reduction is more distinct in the high application (1000 mm) of irrigation water than with the low application (300 mm). The steep slope of the curve in the 0.2 dS/m to 2 dS/m range compared with the higher EC values indicates the importance of the fresh irrigation water as a water source. A large reduction in the wood harvest is predicted (168 t/ha per 1 dS/m EC increase) in the range 0.2 to 2 dS/m at the high application of 1000 mm/year. The rate decreases as the irrigation salinity reaches 5 dS/m. Beyond that the change in the wood harvest stabilises for most treatments, even for the high application rate it is only 20 t/ha decrease per 1 dS/m EC increase. As previously explained, the rate of change is much smaller for low irrigation applications. Similar relationships are predicted for the heavy soil with a flatter slope than for the light soil indicating greater sensitivity to salts in the lighter soils. This is understandable as a given amount of salt is more detrimental to plants in a light soil because its lower water holding capacity results in higher salinity concentrations in the soil compared with a heavy soil.

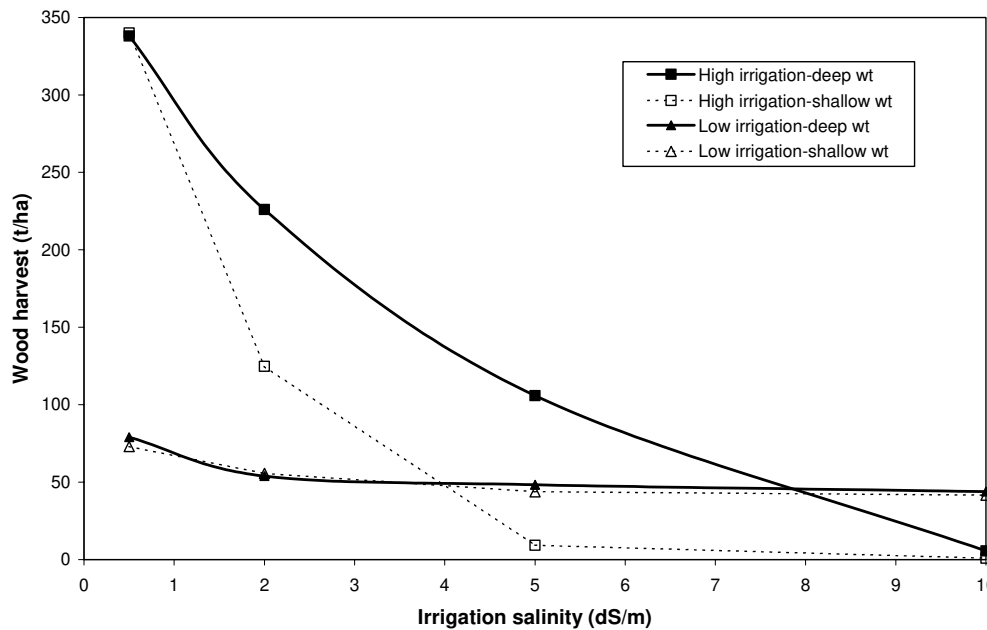


Figure 22. Effect of irrigation salinity on wood harvest of *Eucalyptus grandis*, on light soil at Kerang with 2 dS/m groundwater.

Groundwater use by the trees follows a similar relationship as that observed for the Tatura site. Figure 23 is an example of the inflow into the plantation as a measure of tree groundwater use for Kerang at the age of 15 years after planting on a light soil with a deep watertable and a low amount of irrigation with fresh water. The decrease of water use with increasing groundwater salinity is more distinct from 2 to 5 dS/m than beyond 5 dS/m.

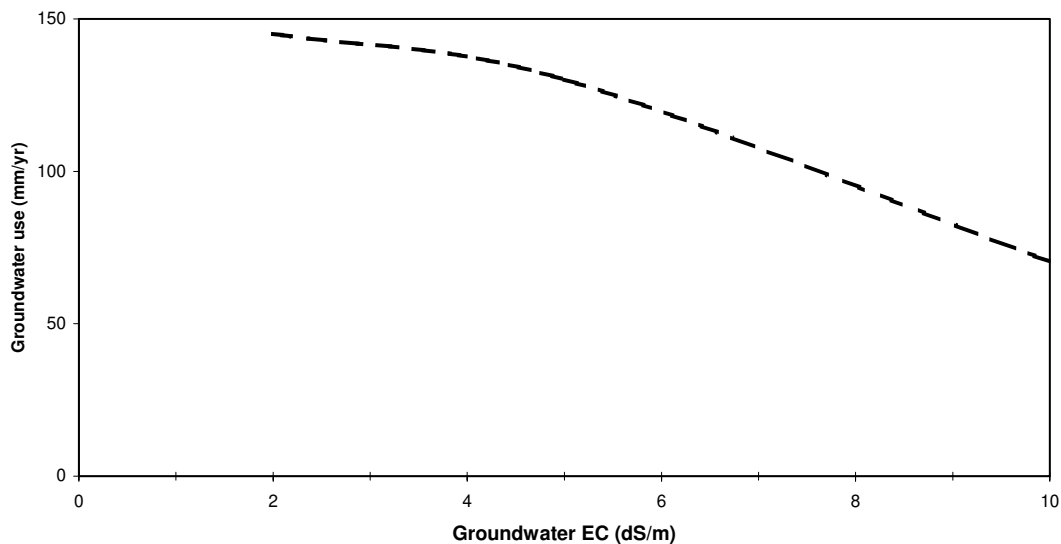


Figure 23. Effect of groundwater salinity on groundwater use of *Eucalyptus grandis* on light soil, watertable at 4 m with different irrigation amounts (at 15 yrs) at Kerang.

As irrigation amount increases, the relationship between groundwater use and salinity would indicate the same trend but with a flatter slope. It should be noted that in different years and under different conditions the above relationships may change, and the curves may shift according to the specific situation.

The dynamics of salt build-up and movement in the profile can help us understand the processes occurring in the soil rootzone environment. One interesting aspect of the salt accumulation is the

location of the salt bulge, which is shown in Figure 24, at the end of year 10 and 20, for a high irrigation regime with fresh water on a light soil, with a deep watertable. Salt build-up of up to 17,000 mg/L (approx. 26 dS/m) is obvious at the end of year 10 for the high groundwater salinity and less for the low groundwater salinity, but at the end of year 20, the two bulges reach the same maximum salt concentration. The total salt (the area under each salt profile curve) being higher in the case of high groundwater salinity.

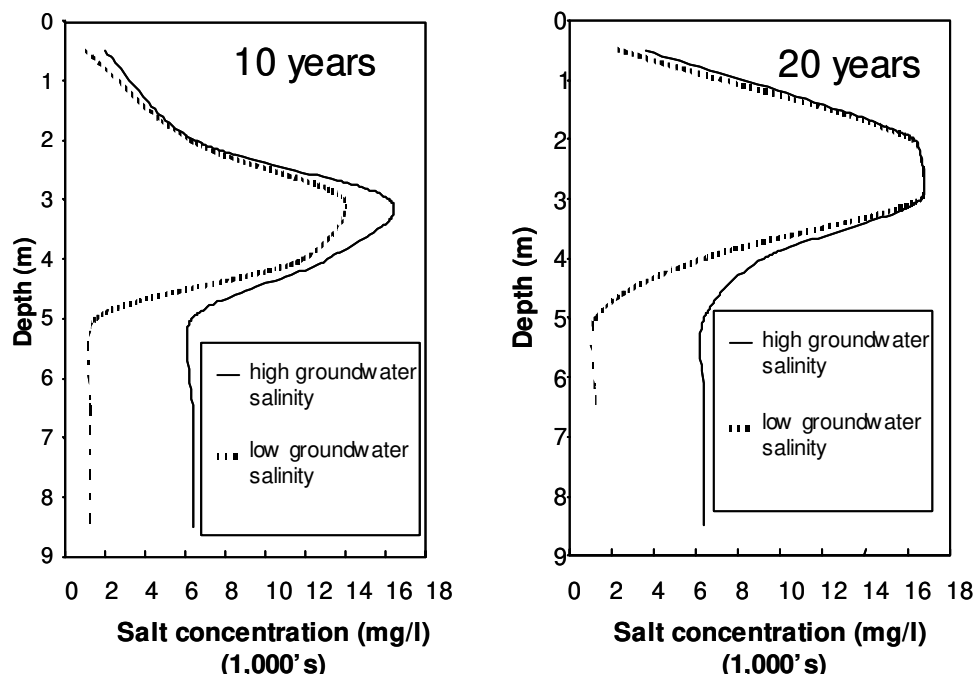


Figure 24. Salt profiles at the end of 10 and 20 years of growth for *E. grandis* on light soil, watertable at 4 m depth at Leeton (high irrigation).

The position of the salt bulge corresponds with the root distribution of the trees in the profile, as the trees adjust their roots upwards with time to make more use of fresh irrigation water available to them in this scenario.

Sustainability

The question of sustainability of the system and how long it takes for different conditions to show the impact of waterlogging and secondary salinity can be studied by the trends in biomass production and watertable position over time. Figure 25 shows selected examples of the response of the plantation to environmental and management factors.

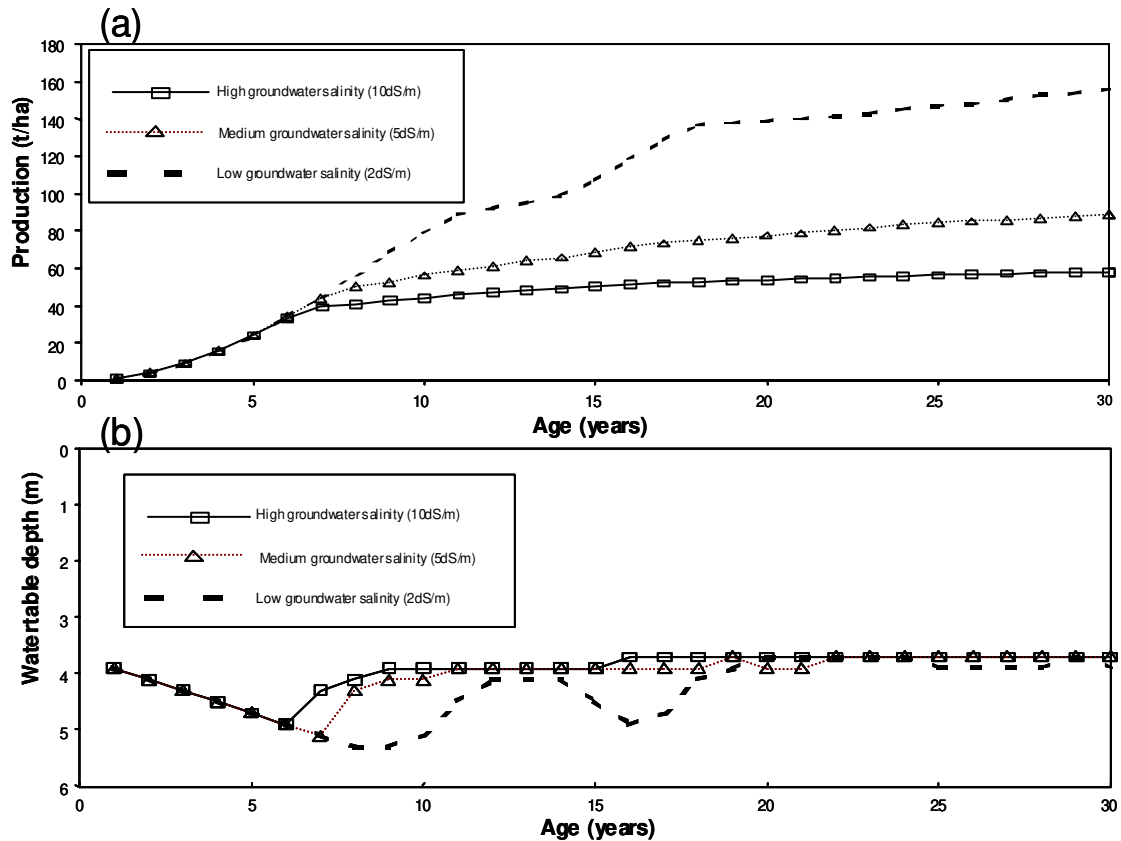


Figure 25. Wood production (a) and watertable prediction (b) for 3 groundwater salinity levels for *Eucalyptus grandis* on light soil, watertable at 4m depth and no irrigation at Kerang.

The graphs are for the no irrigation option at Kerang and indicate that wood biomass production (Figure 25a) increases with time after planting and reaches a maximum after 17 years, depending on the salinity of the groundwater, and then starts to level off. This is when the watertable (Figure 25b) starts to rise to the same level as under the surrounding pasture. For the low salinity level of 2 dS/m, this happens after 17 years with a biomass of about 137 t/ha. For the higher salinity levels of 5 and 10 dS/m, the reduction in growth occurs after 8 and 7 years, respectively. In the case of the low salinity groundwater, trees are able to overcome the first fall in growth (LAI drops to 1) and partially recovers after a few years (to LAI of 2). However, in the long term trees cease to grow and this causes the eventual rise of the watertable. Irrigation with moderate salinity (5 dS/m) on the same soil, watertable depth and salinity would severely limit the growth and production of trees.

Another way of examining the sustainability of the system is to study the trend in the current annual increment (CAI) with the yearly biomass production. In most scenarios CAI increases each year after planting, until it reaches a maximum value, which depends on the position of the watertable and salinity levels of groundwater and irrigation water, after which it starts to decrease or level off.

Figure 26 is an example of CAI predictions at Leeton with a three year moving average trend line for high groundwater salinity level. Three scenarios with respect to irrigation are compared: high irrigation with fresh water (high_fresh), high irrigation with moderate salinity of 5 dS/m (high_med), and the no-irrigation option. For these three scenarios the maximum CAI's are reached after 9, 6, and 5 years respectively (Figure 26a). Note, a rise of CAI to a peak value at 5-15 years of age or so, followed by a decline, is absolutely normal behaviour for the best, healthiest and most sustainable of plantations (it reflects a natural sigmoidal growth curve). This is also evident from the watertable predictions (Figure 26b). In the case of the high irrigation scenario, the application of fresh water for tree water use and its leaching effect delays the process of excessive salt build-up under the plantation for a few years. However, in the long term the trees respond to the salt by decreasing water use,

growth and production of biomass, which is observed in the long term watertable rise after 11 years. With low groundwater salinity, this process of salt accumulation would slow down and the response is prolonged by two to five years before the rising of the watertable. The high irrigation with moderate salinity generates a quicker response to salinity and watertable rise in approximately five years and maintaining the low growth and production thereafter. Similar behaviour is predicted for all three locations.

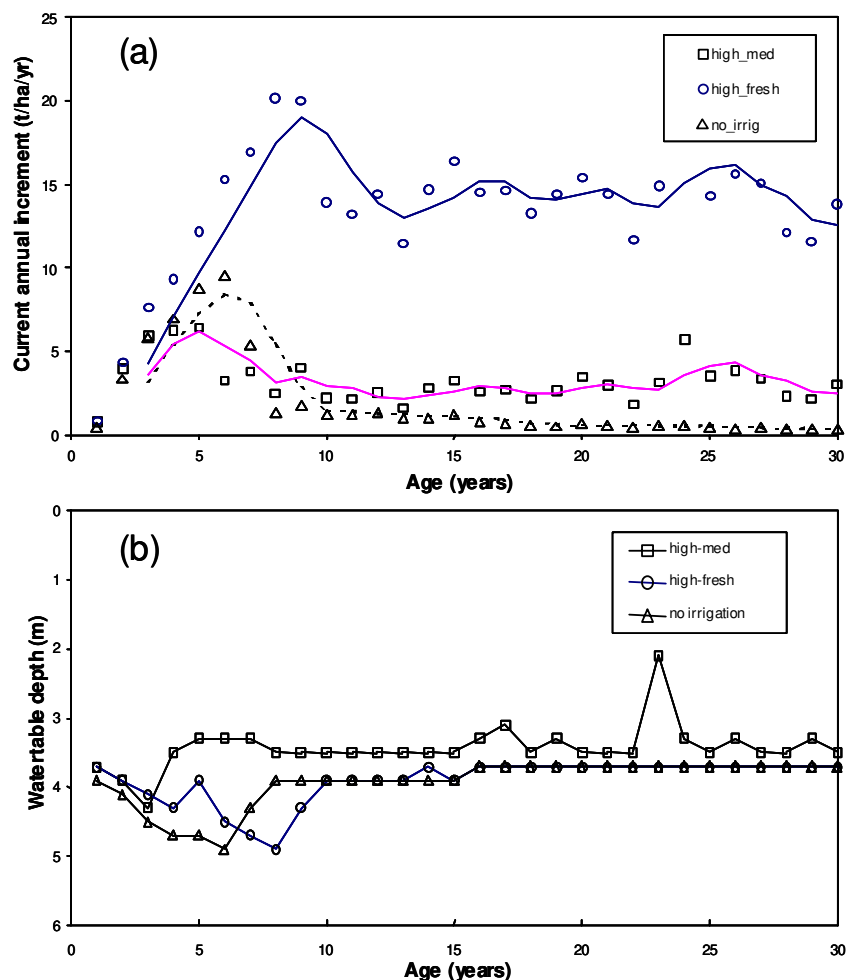


Figure 26. Current annual increment (a) and watertable prediction (b) for three irrigation regimes for *E. grandis* on light soil, watertable at 4 m depth at Leeton.

At the Tatura site there seems to be a delay in this process of a few years (4 years for high irrigation with fresh water) because of higher rainfall, less demand, less LAI and a slower growth rate and higher watertable, especially in the first 15 years at this site as discussed before. The long-term simulations suggest that the time expected for plantations to show the impact of salinity will mostly depend on the irrigation management, soil hydraulic properties, and salinity of both irrigation water and groundwater. In soils with low hydraulic conductivity the response time for the watertable rise is much longer, even though the trees LAI and production might be very low (LAI as low as 0.5) for some years before the watertable rise. With a high irrigation of fresh water in lighter soils, we would expect a period of 9-13 years (depending on groundwater salinity) before effects of salinity would be evident as a reduction in growth. A low application of low irrigation salinity, or no irrigation, would shorten that time to approximately 6-9 years. The scheduled irrigation with fresh water seems to indicate good growth, (CAI of around 28 t/ha/yr, and LAI of 6). The growth parameters will rise and fall as a plantation ages. This is due to ample fresh water available for tree water use and frequent leaching of salt in the rootzone. It should be noted that these high applications of water (up to 1700 mm/yr) would have some effect on the surrounding land due to lateral and vertical drainage (as

outflow from the plantation) and the salt exported with it, this has not been taken into account in these simulations.

To explore the long-term behaviour of trees with scheduled irrigation and fresh water which seems to give optimum production results, the wood biomass production and inflow predictions with low (2 dS/m) groundwater salinity for 30 years of simulation are compared at two sites: Tatura and Leeton (Figure 27).

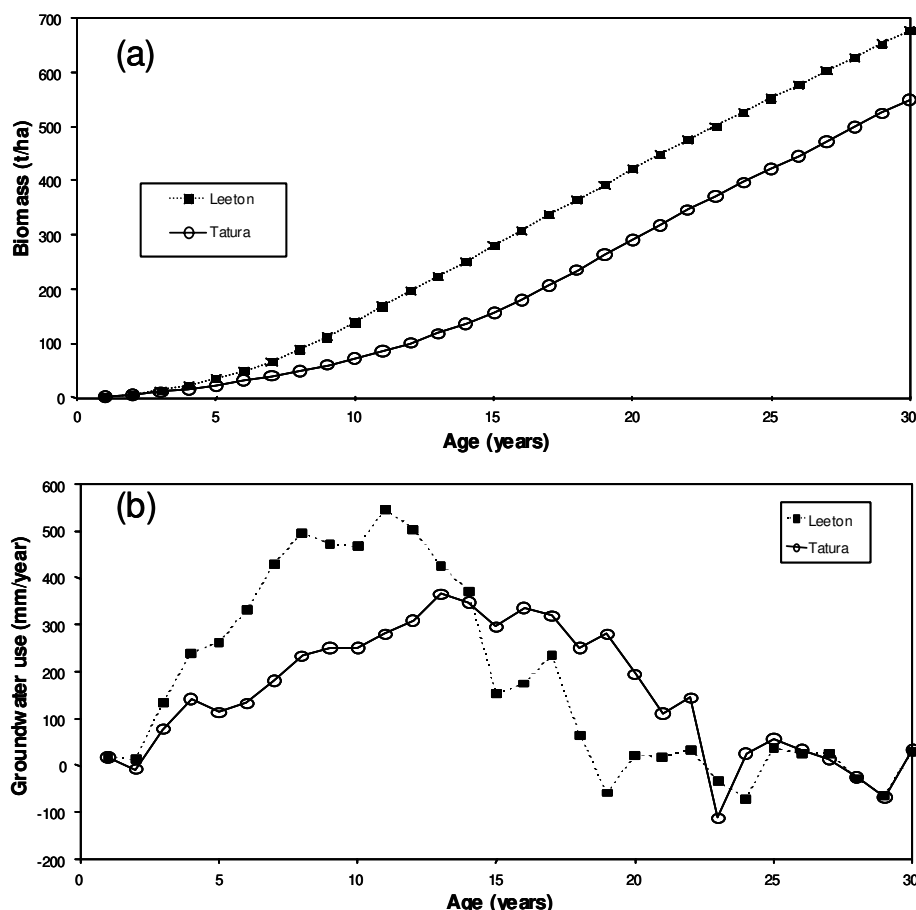


Figure 27. Wood biomass production (a) and groundwater use (b) for *Eucalyptus grandis* on light soil, scheduled irrigation with fresh water, watertable with low salinity (2 dS/m) at 4 m, at 2 sites, Leeton and Tatura.

Drainage out of the bottom of the plantation, including lateral drainage and recharge to the deeper groundwater system, is shown as negative groundwater use. Although the cumulative production continues to increase, groundwater use by the plantation decreases sharply after about 13 years at Leeton, when tree water use would start to show the effects of salinity and waterlogging. The location of the watertable for these simulations is shown in Figure 28. The trees initially lowering the watertable approximately 1 m over the first 10 years: after this time the trees are no longer effective in controlling the watertable.

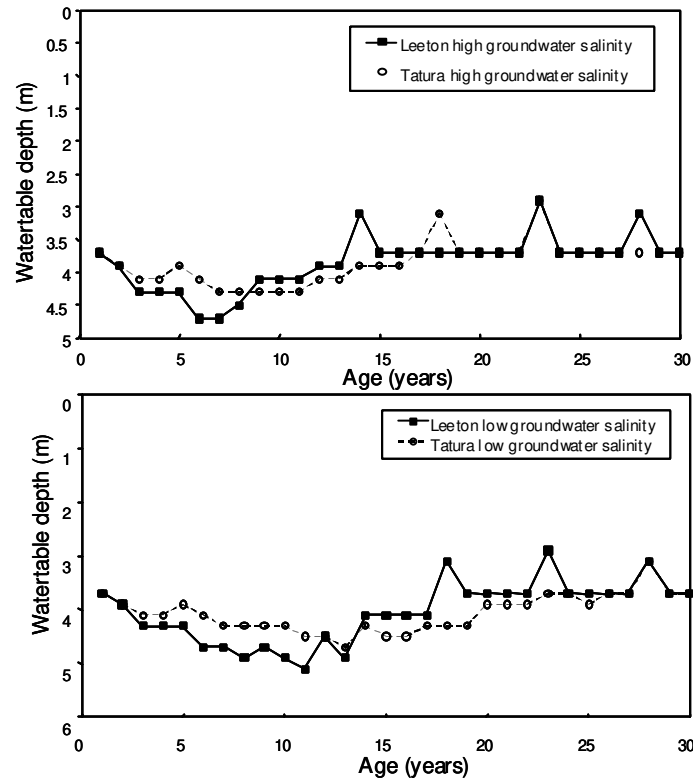


Figure 28. Watertable position for *Eucalyptus grandis* on light soil, scheduled irrigation with fresh water, for low groundwater salinity initially at 4 m depth.

In the Tatura case, the production curve and groundwater use are less than those in Leeton and Kerang (only Leeton is shown here for comparison). The watertable predictions for the first 15 years in Tatura are higher than for other locations, and that causes a delay in establishing growth in early years. However, because of less irrigation (lower moisture deficit) in the second half of the 30 year period the watertable does not rise as high as in other locations and that causes the CAI in production to rise to the same level as other two locations (~ 28 t/ha/yr,) (Figure 29).

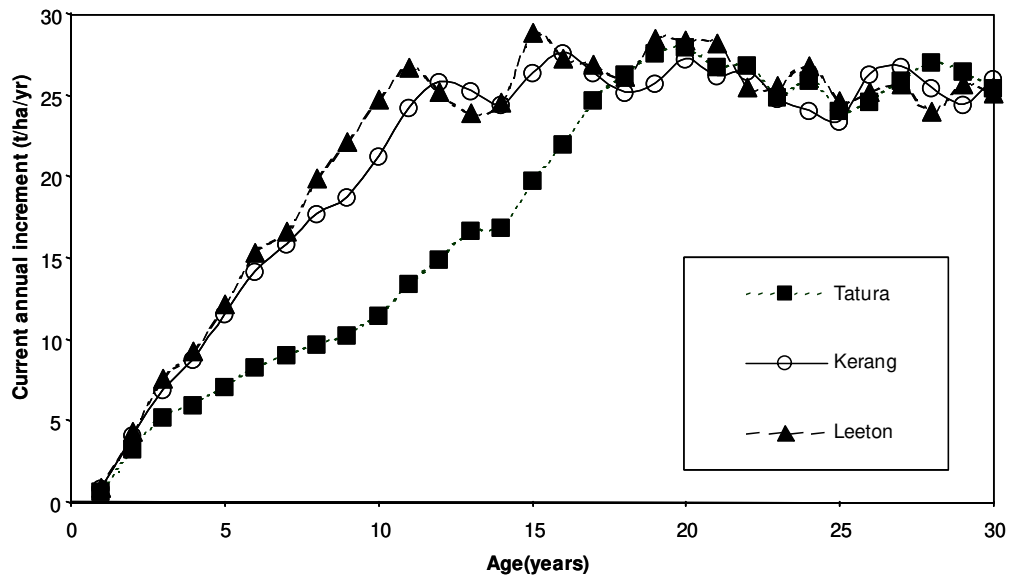


Figure 29. Current annual increment (CAI) for *Eucalyptus grandis* on light soil, scheduled irrigation with fresh water, high groundwater salinity and initially at 4m depth at two locations.

It should be noted that the extra irrigation applied in these scenarios (i.e. scheduled irrigation with up to 1,700 mm/yr net) triggers more growth and production at the cost of lateral or vertical drainage, which carries salt with it as well. For example, with scheduled application of fresh irrigation water on a light soil, there would be approximately 400 mm drainage per year with 26 t/ha of salt exported out of plantation over 30 years. If irrigation water contains a low amount of salt (2 dS/m) these exported values increase to 2,700 mm and 225 t/ha during a 30-year period. This extra salt and water will eventually end up in the surrounding land, which is beyond this modelling exercise, but can be seen as a loss from the 8.5 m profile under the plantation. Thus, if we consider the issue of sustainability, there seems to be a limit to the effectiveness of the plantations in using groundwater for production and lowering the watertable. Where that limit is, depends on many factors some of which are beyond the control and management practices currently available. Economic analysis should help in deciding on the viability of each system to reach a balance between production and the environmental benefits or losses.

Economic modelling

Data processing

The economic model combines biophysical results from APSIM with economic data and other assumptions to calculate economic results. The biophysical inputs are read from an Excel or ACCESS database which has been output from APSIM. The economic model converts them to variables of economic relevance, combines them with monetary value data, and outputs economic results in terms of annual net benefits. It is in the form of an Excel workbook with separate sheets for various components (eg. costs, wood production, river salinity etc), and with processing and calculations done in Visual Basic for Applications modules¹.

Each record in the database of APSIM results relates to a particular scenario and a particular year (from 1 to 30) with results for the following subset of the variables produced by APSIM:

- wood biomass/ha
- wood harvested/ha
- no.stems/ha
- watertable depth under trees (m)
- watertable depth at varying distances from edge of trees – 5, 10, 20, 50, 100m
- distance to point of no effect on watertable
- volume of discharge into plantation zone (mm/yr)
- volume of irrigation (mm/yr)
- total salts stored under plantation (t/ha).

Each scenario is identified by a code made up of 8 digits where each digit represents the value of a factor as per

Table 4. The total number of scenarios provided for *E. grandis* was 2,106 or (3 x 3 x 3 x 2 x 1 x 3) x (1+ 3 x 4).

Table 4. Scenario codes

Factor:	Location	Soil type	GW Sal	WT Depth	Species	Spacing-thinning	IrrVol	IrrSal
Factor nr.:	<u>1</u>	<u>2</u>	<u>3</u>	<u>4</u>	<u>5</u>	<u>6</u>	<u>7</u>	<u>8</u>
Factor code								
0							no irr	no irr
1	Tatura	light	2	2	<i>E.camaldulensis</i>	no thin	low	0.2
2	Kerang	medium	5	4	<i>E.grandis</i>	light thin	high	2
3	Leeton	heavy	10			heavy thin	smart	5
4								10
No. of variations	3	3	3	2	2	3	3	4

¹ The file is available on www.users.bigpond.com/bill.loane/APSIMEc.html

The routines are partly derived from the earlier FARMTREE model but have been heavily modified to suit the needs of this project and new data formats available. (Loane B, The FARMTREE Model - Computing financial returns from agroforestry, *Proceedings of Australian Forest Growers 'Faces of Farm Forestry' 1994 Conference*, Launceston, May 1994. www.users.bigpond.com/bill.loane/FARMTREE.html)

Any scenario run can be processed individually in the economic model, producing detailed intermediate and summary or final results. The full set of APSIM data are run as a batch, with only summary and final results for each scenario being output in a new financial results table.

Calculation routines

Costs

The base case, from which the effects of each tree-planting scenario are implicitly measured, is irrigated agriculture without trees, with the irrigated land protected by a groundwater pump, which keeps the watertable stable at 2 or 4 m. The pump produces saline water which may be partly diverted for re-use on pasture but leaves surplus saline water which is sent to the drain.

In the tree scenarios, the plantation is added on a parcel of unirrigated lower-value land adjacent to higher-value irrigated land. This requires some new irrigation infrastructure for the trees but involves a lower opportunity cost of land. If the trees were planted on high-value irrigated land, the cost of land would tend to outweigh the saving in irrigation, and preliminary simulations indicated that there would be little additional agricultural benefit from watertable drawdown. Hence the focus is mainly on the salt disposal benefits of the plantation.

The APSIM runs assumed a 300x100 m block of trees (3 hectares), although there are potential economies of scale from larger areas if sufficient water is available. Establishment costs include ploughing, ripping, mounding, weed control and fertilising similar to those used in the DNRE's Trees for Profit Program trials in irrigation areas. The cost of seedlings and planting depends on the spacing and hence total number of trees, using the three spacing options specified in the chapter on APSIM modelling.

The cost of irrigation infrastructure is based on the capacity of pumps required to match the assumptions concerning rate of application of irrigation water and plantation area. It is set up to vary with other factors such as distance from dam to plantation although it was held constant in runs for this project.

In batch runs for comparing scenarios, costs are held constant at a best-guess level except where variation is appropriate to capture the effects between different scenarios. For example, for different spacings between trees, costs of plants and planting and consequently biomass would vary, but cost of pumps for irrigation would be constant.

Water costs

For fresh water irrigation, the cost of water is assumed to be an average market price of \$56/ML, on the assumption that it is additional water purchased on the market or else could have otherwise been sold. At the time of writing, the actual charge by the water corporation is around \$25/ML. The cost of saline water is taken as zero, assuming that only surplus water from pumped groundwater or drainage is used, after any opportunities for re-use on pasture (mixed with fresh water to achieve an acceptable salinity level) have been taken.

Wood production

The biomass data from APSIM is converted to size of individual trees and logs to allow financial valuation. Broad summaries are done for standing trees at each year, but detailed calculations are done only at selected harvest times, namely thinning and final harvest. All APSIM runs simulated a fixed period of 30 years, but earlier harvest times are tested for a limited range of scenarios in the economic model.

Stem volume is estimated from biomass, wood density and branch fraction. Mean stem diameter at breast height (DBH) is estimated from biomass according to allometric relationships (see Appendix 5 for these and other functions used). The size distribution of diameters is then calculated according to a Weibull frequency distribution, with parameters based on studies of young plantation eucalypts. For harvest calculations, the trees are grouped into 10 diameter classes.

Taper functions are used to express the reduction in stem diameter with increasing height up tree. These are used in an iterative process to find the top height which is consistent with the given volume and diameter at breast height.

Logs: The sizes of individual logs which can be cut from each tree size class are calculated from the taper functions, DBH, height and log specifications (required diameter, length). The volume calculations for individual logs use the formula for a cylinder.

Wood stumpage prices increased from \$10 to \$50/m³ with increasing log diameter as set out in a schedule with 5 log diameter classes (Appendix 5). There was no attempt to identify particular types of market or prices for different products such as pulpwood, roundwood and sawlogs. The price would depend on the best market available at the time of the future harvest, which could involve either delivery to markets in larger centres, local processing industry, or on-farm use.

The value of each log is simply price times volume, and total wood revenue is obtained by aggregating across all logs and trees.

Mean annual increment in merchantable wood volume (MAI) is calculated as an indicator of wood productivity. It should be noted that volume of merchantable wood is close to volume of total stemwood for larger trees, but is much smaller in relative terms for very small stems.

Agriculture

The overall effect on the farmer's agriculture is the sum of:

- the loss on the area occupied by trees and
- any gains from watertable reduction nearby.

The value of any watertable depressing effects of trees was based on the output from APSIM of the watertable depth at several distances outside the plantation edge: 5, 10, 20, 50 and 100 m. These were used to define zones bounded by inner and outer rectangles within which the area was calculated and the agricultural production loss was calculated. The calculated effect on agricultural productivity of varying watertable depths and salinity was based on a relationship derived from a simulation study by Jolly *et al.* (1999) (shown in Appendix 5). Research at Tatura indicates there is no unique watertable height / productivity function, but the relationship found by Jolly *et al.* (*ibid*) is used in the absence of anything known to be more appropriate.

The increase in agricultural production (in tonnes) in each zone is multiplied by the operating margin per tonne for the crop, to derive the value of agricultural benefit from the lowered watertable. These totals are added across all the zones, and the total is then divided by the area of trees to get the value of the gain per hectare of trees.

The trees are assumed to receive no benefit from any groundwater pump in the vicinity, although the watertable level is assumed to remain at the initial (equilibrium) level in the absence of trees.

Downstream effects

The effects of plantations are calculated on the assumption that, in the absence of trees, the excess saline water from drainage or groundwater pumping would have been sent into the drains, streams and eventually the Murray River system where it would have created damage or costs downstream. The cost of damage from saline water to agriculture, industry and residential water-users in the Murray River system has been estimated for the Murray-Darling Basin Commission (MDBC) as \$93-142,000 per year per additional EC of salinity at Morgan, South Australia². The MDBC has then estimated the impact of quantities of salt entering the river in various reaches along the Murray River. Such estimates have been used to put a value on the benefits from drainage schemes diverting salt from the river to evaporation basins, and for a study "Salinity impacts of water trade – rapid assessment tool". Similar figures are used here to represent the savings from the use of saline water on trees as opposed

² Over 90% of salinity impacts of measures/events in the Murray and Murrumbidgee valleys, in terms of both agriculture and domestic and industrial water supply, are experienced in South Australia. Gutteridge Haskins & Davey Pty Ltd, Salinity Impact Study, for Murray-Darling Basin Commission, Feb. 1999.

to export downstream. As the MDBC costs relate to salt actually entering the river, an adjustment was made to allow for diversion or reduction in salt loads between the tree site and the river. The data and assumptions used are shown in Table 5 below.

Table 5. Data and assumptions used to estimate the savings from the use of saline water on trees as opposed to export downstream. *Source: Oscar Mamalai, MDBC, pers.comm.

Location of trees	% salt reaching river	River reach	Economic Impact of salt (\$/tonne entering river) *	Net impact \$ per tonne salt at tree site
Tatura	50	Tocumwal to Echuca	26.4	13.2
Kerang	70	Torrumbarry to Swan Hill	45.5	31.9
Leeton	20	Swan Hill to Euston	49.3	9.9

The quantity of salt diverted by the trees is calculated from the salt content of the irrigation water used, as shown in the following example:

- trees are irrigated with 1000 mm of saline water in a year from a pump at salinity level of 5 dS/m
 - Volume of water used = 1000mm x .01 = 10 ML per hectare of trees/year
 - Salinity of water = 5 dS/m x 600 = 3000mg/L
 - Salt load in water used = 3000 mg/L x 10 ML/ha x .001 = 30 tonnes/ha/year
- If trees are at Kerang, benefit of keeping salt from river:

= \$31.9 per tonne salt at site x 30 t = \$957 /tree/ha/year.

The cost of damages or diversion is largely a community cost rather than falling on the farmer who exports the salt, but a portion is borne by the farmer through irrigation levies. Irrigation farmers who export salt partly pay this cost through a levy for salt interception costs, but this covers only the operating rather than capital costs, except that new irrigation developers are required to pay the full costs. The remainder of the cost is borne by the wider public and is an external cost relevant to a socio-economic analysis, if not a private financial analysis from a tree-grower's viewpoint. Hence, disposal to trees represents a saving to the community, which is at least partly transferred to the irrigator through savings on charges for salt export.

Irrigation farmers are increasingly using part of their saline drainage or pumped water for re-use on their crops. This generally requires dilution with fresh water to reduce the average salinity content, as a threshold level before harmful effects may be around 0.8 dS/m (³). For example, for 5 dS/m water, this would require a volume of fresh water 7 times the volume of saline water. Such re-use is limited by on-farm availability of resources. Where farms still have an excess of saline water for disposal, the plantation use tested here is a relevant option.

Net Values

Financial data for costs, prices and values per unit are combined with the above physical outputs to calculate benefits and costs and net benefits in each year (cashflows). Net benefits are the sum of wood revenue, agricultural savings and river salt benefit, less direct costs and agricultural losses. Expressing the various effects in monetary terms allows them to be added and netted out in one unit, thus allowing trade-offs between different positive and negative effects to be evaluated. All costs and benefits are expressed in real terms - that is, constant dollars of the starting date.

3 From 800EC (0.8dS/m) it becomes increasingly difficult to manage irrigation and at this level, damage to tree crops has occurred. From the point of view of irrigation, the recommended upper limit for water quality is 2,300 EC, (MDB Ministerial Council, *The Salinity Audit of the Murray-Darling Basin*, 1999, p.21).

Aggregates

The overall financial results are presented in two ways:

- net Present Value (NPV), which is the sum of discounted future net benefits
- annuity value of net benefits (annual equivalent income) per hectare of trees. The annuity is the equal annual amount paid every year over the life of the project which has the same total present value as the project's cashflows when both are discounted to the beginning.

Annuities, as well as NPVs, capture the effect of discounting, that is, giving lower weight to effects in the more distant future. The discounting of future values is justified by people's preference for current rather than future consumption, and also by the rate of return the capital could have otherwise earned in other uses. A NPV or annuity value greater than zero indicates that the project is worthwhile as it covers all costs including agricultural land and capital. A discount rate of 5% per annum was used.

Annualised figures have been used here as the focus for comparing different options, as they are more readily understood and compared than Net Present Value, especially in an agricultural context and for comparisons between different harvest periods.

Net results

For the great majority of the 2,106 scenarios run with *Eucalyptus grandis*, a negative net economic return resulted from the modelling at a 5% real discount rate. This was generally due to high establishment costs for trees and irrigation, together with salt accumulation and poor growth with more saline water or else high costs for fresh water. However, some positive net benefits were found – the scenarios with positive results all used scheduled (“smart”) irrigation on land with the deep 4 m watertable, and medium irrigation salinity at 2 or 5 dS/m, on light (or medium) soil. These achieved a near optimal balance with good wood production (from MAIs in range 20 to 35 m³/ha) and high savings on river salt (see Figure 30).

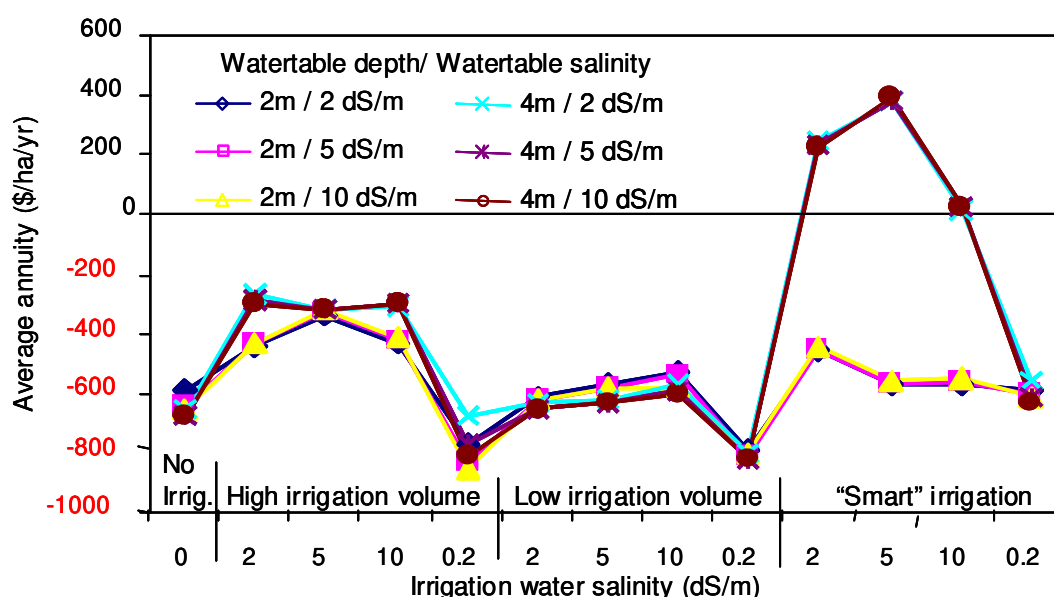


Figure 30. Net Benefit Annuity for various depth to groundwater and groundwater salinity scenarios, on a light soil with heavy thinning at Leeton.

The annuity results ranged from a top of \$385/ha/yr (equivalent to an internal rate of return of 8%) to a loss of \$1100, although not too much significance should be placed on the exact numbers output by the model, but rather on the broad magnitudes and relative values.

The main components of costs and benefits are considered below followed by the effect of each of the 8 scenario factors on net benefits is discussed.

Results by major components

Out of the five cost and benefits components included, the three dominant ones in the comparisons were costs, wood revenue and river savings, while agricultural savings and costs were less significant (in terms of variations between scenarios, although still important in absolute terms).

Costs

The negative economic effects on adding the trees to the pre-existing agricultural configuration are:

- **costs of trees** – establishment costs around \$1,350/ha, plus maintenance costs with net present value (NPV) of \$1000, plus pruning for thinned options costing \$1300
- **cost of extra irrigation equipment** – larger dams for temporary storage, delivery system over 1 km, filtration and land levelling are required to extend the irrigation system to the trees, with cost of \$4,040/ha, with further annual costs of \$190/ha/year.

The establishment costs are considerably higher than for rain-fed plantations which are typical for commercial forestry.

The irrigation infrastructure was costed at a fairly high standard with professional management. It includes a storage dam for the saline drainage water, pump, filtration unit, and delivery system to trees, with laser levelling, contour furrowing and dripline irrigation for the plantation. After that, annual management costs, are much lower but at \$200/ha/year are relatively high compared with commercial plantations due to the irrigation needs.

- **cost of land** – this is a major negative element. Use of high-value irrigated horticultural land worth more than \$10,000/ha would render the tree options uneconomic. But use of lower value pasture or cropping land, at \$3000/ha in the 2 m watertable protected land case, is assumed here, making net returns more viable.

While the above costs are high and important in determining overall profitability or net benefits, they vary little between different scenarios regardless of site or tree project.

- **cost of water** - for fresh (channel) water irrigation, water costs are a major additional cost that is not incurred with the saline options. For example, with high-volume fresh irrigation, the costs are up to \$560/yr, with a present value over 30 years of \$8,600.

Wood

Wood revenue is a critical variable which varies widely from negligible to \$600/ha/year depending on tree growth. The revenue depends on:

- volume of wood, which is derived from APSIM's bio-physical estimates, and varied widely – directly with access to water, and inversely with salinity, and
- stumpage prices.

MAIs

The physical rate of wood production over the trees' life for different scenarios was represented by their mean annual increment (MAI). The predicted MAIs in the better economic scenarios were 25-35 m³/ha (Figure 31). These are high compared with the experience of commercial rain-fed plantations, but derived from unusually high rates of watering (rain+ irrigation). They are consistent with MAIs observed in the better irrigated plantations up to 10 years old, but maintaining such growth over 30 years is problematic. [They may also over-estimate merchantable wood by not making enough allowance for defective wood.]

On the other hand, alternative model runs with 3PG suggest that APSIM may underestimate growth of plantations on 2 m deep watertables with medium salinity water, especially on heavy soils. These scenarios showed quite low MAIs (under 12) in APSIM and consequently poor economic results. A large difference, for example, was seen in a case of heavy soils with high-volume 2 dS/m irrigation, where APSIM predicted MAI of about 3 while 3PG suggested 17. That scenario was highly negative

with APSIM data, but upgrading the volume estimates on the basis of 3PG could lift it into the economic range.

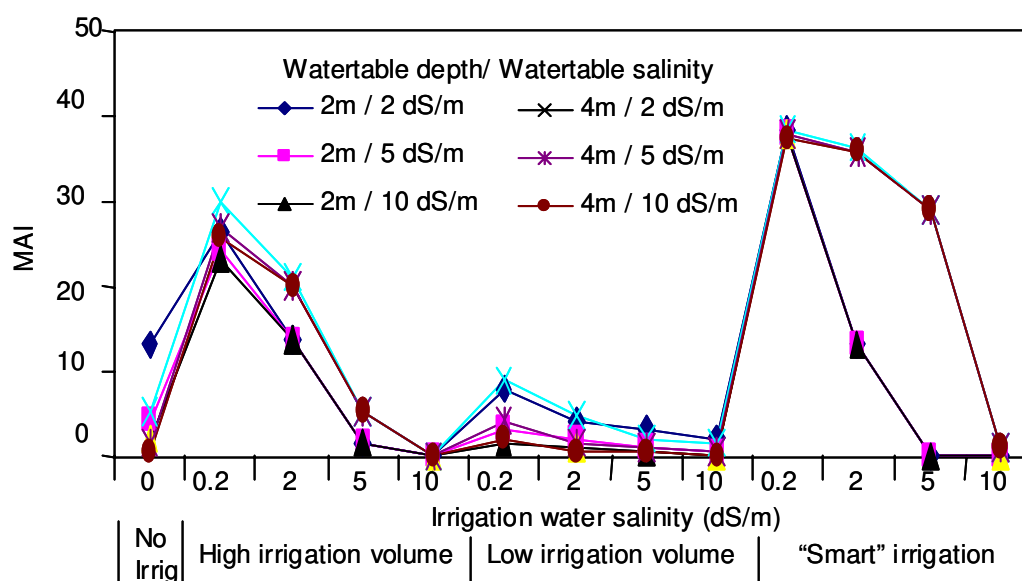


Figure 31. Mean Annual Increment in wood, for various depth to groundwater and groundwater salinity scenarios, on a light soil with heavy thinning at Leeton.

Prices

Although the price schedule was fixed, the average price turned out substantially higher for higher volume plantations, as they provided larger diameter logs. The average price varied from \$21/m³ for a plantation with MAI of 15, to \$38 for MAI of 29, and up to \$50/m³ for MAI of 35. The bulk of the volume for large stems is in the bottom more valuable logs, and average stumpage increased more than proportionally with volume. However, there appears to be an over-estimation of average prices for the high-MAI stands due to over-estimation of the weighting towards the larger logs in the distribution. The heavily thinned stands were assumed to be pruned, which also adds value to the lower logs. No allowance was made for future increases in real prices as some other forestry studies do, as the prices are in any case speculative in those irrigation areas where there has been no established forestry, but that is a possible source of improvement.

Discounted wood revenue

With low salinity water (2 dS/m), the higher value pruning option can return \$18,000 after 30 years. But discounting at 5% pa has the effect of reducing the harvest revenue by a factor of 77% when brought back to a present value at the start of the project. These returns would not be sufficient to outweigh the costs and make the project economic by themselves before consideration of salinity benefits.

River salt

The river salt benefits are another source of widely variable benefits. With low-salinity water, the river benefits are \$180/ha/year, which makes a useful contribution to the economics of the project, but not sufficient to give a net positive return. With medium salinity water, these benefits at \$400/year become considerable. To a limited extent the salinity benefits rise directly with higher wood revenues, insofar as a higher volume of water of moderate salinity produces higher wood volumes as well as river savings. Where the irrigation salinity is too high the trade-off between salinity benefits and

wood production becomes obvious. The river salt benefits are surprisingly high in the case of high-volume high-salinity irrigation water, up to \$800/ha/year, but tree growth soon declines.

The other two components are more stable across different scenarios:

Agricultural losses

The opportunity cost or rental cost of the land occupied by the trees was a significant addition to total costs, at around \$150/ha/year (present value of \$2,300), but differed little between the different scenarios as explained above in relation to watertable depth. Hence it had little effect on the ranking of various scenarios. This cost implies a fairly low land value for irrigated regions, but assumes that the trees would not be placed on high-value irrigated land, but lower value unirrigated land, adjacent to irrigated land. By the same token, this means that costs are required for new irrigation facilities.

Agricultural benefits

These turned out to be negligible, given the output from APSIM of watertable-lowering effects outside the plantation and the functions for agricultural productivity referred to above. Broadly, the smallness of effects was due to the fact that significant reductions in productivity below potential are only indicated in Jolly *et al.*'s (1991) relationships as watertables become shallower than 2 m, with groundwater salinities of 5,000 mg/L or greater, and only for clay soils. With the simulations in this project, the significant lowering of watertable was generally limited to 20 m from the plantation, and the trees produced lowering of the initial 2 m watertables by a maximum of 3.8 m at a distance of 10 m outside the plantation in a low salinity groundwater area. This only improves pasture productivity by a few percent. With the initial 4 m watertables, pasture is safe from saline groundwater even before the trees. Unless the trees are in the middle of protected irrigated land, their watertable lowering effect will be limited to any side that is adjacent to such land. In some cases where high volumes of water were applied in a saline situation, watertables under and around the trees rose rather than fell, as the trees were unable to use either groundwater or all the applied water.

Effect of scenario factors

The effect of each of the eight scenario factors in the model results is considered below:

Location

Location had little effect on average results, although Leeton and Kerang dominated the top results, and Tatura results were, on average, slightly worse. For example, MAI for best scenario was 29 at Leeton compared with 23 at Tatura. The differences were due solely to the growth differences resulting from climate parameters.

Soil type

The best results were on light soils where greater uptake from groundwater, such as from lateral flow into the plantation, was possible, as a supplement for the rainfall and added irrigation. This, however, only applied to the deeper 4 m watertables. There was a marked contrast, for example, in the no-thin, smart irrigation with 5 dS/m, between light soils with an average⁴ MAI of 17 and heavy soils with MAI around 1. On the shallow 2 m watertable, on the other hand, MAIs for all soil types were minimal - around 1. Note that the difference between light and heavy soils also reflects the aquifer characteristics in supplying groundwater to plantations as discussed in previous chapters.

Plantations on heavy soils⁵ were generally uneconomic. With fresh irrigation water there was less difference in MAIs between the soils; for example, in the no-thin, smart irrigation case, light soils had

⁴ Average here refers to the average of results across all other scenario factors such as location and irrigation management.

⁵ "Heavy" soils in the APSIM scenario runs does not refer just to the inherent permeability of the soil, but also involved limited supply of groundwater from aquifers. Some heavy soils in the Shepparton region are known to have greater availability of groundwater.

an average MAI of 32 and heavy soils around 29. The high cost of fresh water meant that those plantations on all soil types were uneconomic.

Groundwater Salinity

The salinity of groundwater made little difference in the range of the more economic results, but less saline groundwater was better due to the better tree growth. There was some increase in land cost for the lower salinity groundwater but this was relatively small (<10%) owing to the small estimated effect of salinity on agricultural value in the relationship referred to earlier. The average MAI (averaged across all scenarios) was 8.5 for low groundwater salinity (2 dS/m) and 6.9 for high salinity (10 dS/m). In the case of low volume irrigation at low salinity (2 dS/M), there was a greater relative difference in MAIs: 3.1 for low groundwater salinity and 0.7 for high salinity. In the latter scenarios, the MAIs were too low to be of economic interest, due to the high cost of water.

Watertable depth

All the positive economic results involved deep watertables at 4 m. This was due to the growth difference with different watertable depths. In the best cases, with light soil, medium groundwater salinity, light thin, smart irrigation with medium salinity water (2 dS/m), average MAI was 34.4 for the 4 m watertable compared with 10.8 for the 2 m watertable. In the case of fresh water with smart or high-volume irrigation, both watertable situations had high MAIs with little difference between them, however, these were not of economic interest.

The agricultural value of the land (and hence the opportunity cost for tree-growing) was assumed to be slightly higher for the 4 m watertable. The relative values were estimated on the basis of functions for agricultural pasture productivities in saline conditions derived by Jolly *et al* (1998), but the difference between 2 and 4 m watertables was only a few percent, and this was insufficient to outweigh the advantage for tree growth as modelled by APSIM. Significant differences in productivity were indicated in the functions in the range of watertables shallower than 2m and groundwater salinities of 10,000 mg/L or more, but these were outside the range of the APSIM scenarios.

Species

Eucalyptus grandis was the only species subject to full simulation runs, as *Eucalyptus camaldulensis* has not yet been parameterised for APSIM. It is expected that *E. camaldulensis* will perform worse on the scenarios with fresher water and better with the more saline sites and water. *E. camaldulensis* has lower maximum potential growth rates, less straight stems, and less value for mass wood markets, but is more salt tolerant and worthy of further investigation for saline sites.

Spacing

The best results were with thinned stands. This was largely because of the higher initial stocking density (1250/ha) compared with 625/ha for the unthinned regime, so they enjoyed a higher degree of site occupancy for most of the rotation. The higher initial cost of plants and planting is insignificant compared with the gains. Further, the fast growth allowed the remaining trees after thinning to develop into large diameter trees with higher values for pruned logs, sawlogs or large roundwood. This resulted from the stepping in the stumpage schedule for logs from \$10/m³ for the smallest logs with small end diameter between 10 and 20 cm, up to \$55 for the larger logs above 45 cm. Heavy thinning (removing smallest 80% of stems, leaving about 250/ha) was slightly more economic than light thinning (removing smallest 50%) because it took greater advantage of the stepped stumpage schedule.

Irrigation volume

“Smart” irrigation by far surpassed high and low volume options in economic results. This reflected the difference in growth and MAI. Growth with smart irrigation was naturally larger than with low-volume regular irrigation, but was also significantly larger than high-volume irrigation, especially for medium-salinity water, for example, with 5 dS/m water, average MAI was 29 for smart and only 5 for high. Irrigation with high regular volumes (1000 mm/yr = 20 x 50 mm applications) of saline water (5 dS/m or more) resulted in limited growth due to salt accumulation. With less saline water at 2 dS/m, the growth difference was still significant but both were in the commercial range - average MAI

was 36 for smart and 20 for high. MAIs for both were minimal for 10 dS/m water. Low volumes of irrigation (300 mm/yr) with fresh water resulted in low growth and wood volume. The gains in growth from irrigation were insufficient to be worth the cost of water.

The better growth with “smart” irrigation reflected the fact that it often delivered larger volumes of water over the life of the trees (up to 1700mm/yr), and they were delivered with better timing according to moisture deficit and salt leaching needs. In practice, farmers would not deliver precisely the same irrigation amounts as estimated to be needed by the model. Nevertheless, by taking some account of moisture needs, they could achieve better results than by delivering an automatic regular amount. However, negative side-effect of the excessive watering and leaching was net drainage under the plantation; averaging around 350mm/yr for example for the top economic scenario. This tends to defeat the purpose of trees for addressing shallow watertable problems in a sustainable way, unless rules for leaching with more minimal drainage can be found.

Irrigation salinity

Irrigation salinity levels from 2 to 5 dS/m comprised the best positive economic results, with 5 dS/m producing the highest net return, slightly better than 2 dS/m. Both those salinity levels produced both high wood growth and high river savings. There were even a few options with 10 dS/m water in the top 5% of results, but these were marginal as the wood production was very low, and the benefits were virtually all river salt savings, while drainage was high.

Fresh irrigation water (salinity of only 0.2 dS/m) naturally produced the highest MAIs, but was uneconomic as its cost outweighed the gains in wood accumulation. The highest wood MAIs, up to 38 m³/ha, came from high “smart” applications of fresh irrigation water, but at a market price (or opportunity cost) of \$56/ML, the cost was as high as \$900/yr.

Harvest age

Most of the analyses were done with a 30-year rotation period for the plantation, which was the period simulated by APSIM. A few economic scenarios were tested for shorter rotation periods from 10 to 25 years. This offered some hope of gains as the peak current growth rate of plantations is often reached around 10 to 20 years old, and harvesting then takes advantage of the best wood accumulation while avoiding the later period of salt accumulation and low marginal increments in wood volume.

On the limited number of scenarios tested from among the positive economic options, the optimal harvest or rotation age was 30 years. In these cases the MAI as predicted by APSIM was still increasing up to 30 years. Thus, the benefits of deferring harvest (extra wood revenue plus river savings) exceed the extra costs consisting of maintenance (after any pruning has been finished), land rent, and the opportunity cost of capital tied up in the plantation; that is, the interest forgone by postponing the harvest with its accumulated revenue⁶. The higher the on-going river salinity benefits, the lower the wood CAI (current annual increment) that can still justify deferring harvest for another year. It should be noted that as well as the volume increasing, the average stumpage price will increase as log diameter increases. Eventually when the CAI drops too low, it is optimal to harvest, and begin the rotation again.

Another way of looking at this is that the establishment costs for trees and irrigation equipment are high (over \$5,000) and when viewed as an annual equivalent are significantly reduced over longer periods (about \$325/year at 5% interest rate over 30 years, compared with \$482 over 15 years). Hence the average benefits over a shorter period have to be high to match these annualised costs.

The shape of the CAI curve over time is important to the harvest period decision. In some situations, mainly 4 m deep watertables on light soils (which are in the more economic range), both APSIM and 3PG showed CAI being maintained above 15 m³/ha from year 5 through to year 30 (Chapter 5). This would lead to a longer optimal harvest period. On the other hand, in situations with shallow watertables on light soils, APSIM showed a distinct decline in CAI after 15 years, favouring a quicker

⁶ It is economically worthwhile to delay harvest for one more year if the value of the extra benefits exceeds the extra costs. In this case, $(\Delta W + \Delta R) > \Delta C + \Delta A - W(1+i)$ where W=wood revenue, R=river savings, C=direct costs; A=agric.cost; i=interest rate. Or $(\Delta W/W) > i + (C+A-R)/W$.

harvest. On heavy soils, growth in APSIM reduced to zero after about 12 years, although in 3PG CAI was declining but remained above 15 up till age 30. Such differences have major implications for harvest periods.

In many of the scenarios where MAI peaked earlier, deferring harvest by another year brought more extra costs than benefits. However, these generally gave negative net results. The annuity value improved with harvest age in the sense that it became a lower negative amount, but that just indicates that a smaller loss per year is obtained by less frequent replacement of the plantation.

Salt accumulation

Certain other salt movements are incipient physical effects, but have not been attributed an economic value in this study. Salt accumulates under the plantations, especially with high-volume high-salinity irrigation. Stored salt accumulated up to 400 t/ha under the top economic scenario. This generally represents a redistribution of salt from under the agricultural crops to under the trees. This could be a benefit to the crops by moving salt away, but no attempt has been made here to track any effect of changing salinity levels on agriculture.

This salt would remain as a potential problem after the plantation is harvested. If it remained concentrated in the rootzone, it would make growing the next crop more difficult. However, it is likely to be redistributed or diffused further more widely. Due to the inability to predict the long-term salt movements, they are here regarded as broadly self-cancelling.

From one point of view, salt creates costs or problems wherever it is – under crops, or sent to the river or evaporation basin. It can be neutralised under the trees for the life of the plantation, before it reasserts itself. Planting subsequent rotations of trees, perhaps in a different place, may extend the period of neutralisation.

Conclusion

For the great majority of the 2,106 scenarios run with *Eucalyptus grandis*, a negative net economic return resulted from the modelling at a 5% real discount rate. This was generally due to high establishment costs for trees and irrigation, together with salt accumulation and poor growth with more saline water or else high costs for fresh water.

Positive net benefits were found in a limited range of circumstances which nearly all involved scheduled (“smart”) irrigation on land with a deep 4 m watertable, on lighter soils, with medium-to-high irrigation salinity at 2, 5 or 10 dS/m. Many of these achieved a balance of both good wood production (from MAIs in range 16 to 31 m³/ha) and high savings on river salt. Heavy thinning was best among these scenarios, but light thinning and no-thinning were only slightly less economic.

The highest total returns involved higher salinity irrigation water (10 or 5) where the river saving was the dominant benefit and wood production was low.

A number of questions raised above need further investigation before we can proceed with confidence. In particular, the shape of the biomass curve over time needs to be examined, both to determine the absolute level of returns and whether the optimal harvest time could be earlier. It appeared that some scenarios with lower volumes of medium salinity water on heavy soil could be more economic under 3PG although not APSIM simulations. The high drainage rates under smart irrigation appear unsustainable, unless more precise rules for scheduling with less water and drainage can be adopted as a practical matter.

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Appendices

Appendix 1. Kyabram soil hydraulic properties used in the modelling

Soil moisture characteristic data were obtained for Lemnos loam soil (K.A.Olsson, ISIA, Tatura, unpublished data). The smooth Brooks-Corey function was fitted to the data. The saturated hydraulic conductivity data were obtained from *in situ* measurements (disk permeameters, well permeameters, and slug tests) as well as measurements on core samples (Feikema 1995, Connell *et al.* 2000). The soil profile was simulated to a depth of 6 m with four layers of different hydraulic properties.

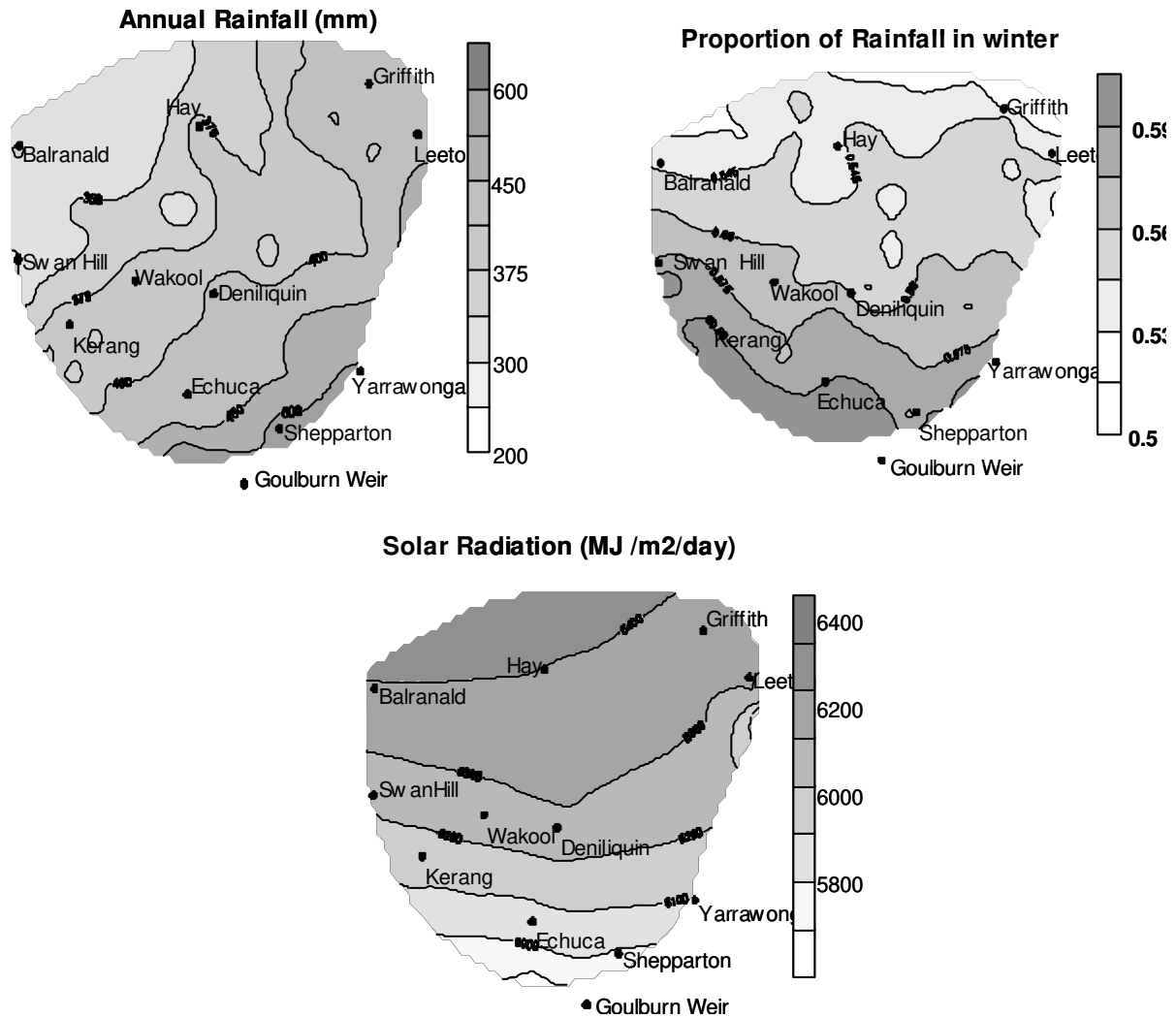
The following table shows the parameters of the smooth Brooks-Corey function for the simulated layers in the profile.

Depth interval (cm)	b	θ_s	Ψ_e (cm)	K_s (cm/h)
0-20	12.5	0.41	-2.3	1.4
20-50	21.5	0.39	-8.2	1.2
50-100	24.2	0.39	-6.4	0.2
100-600	26.5	0.41	-5.2	0.2

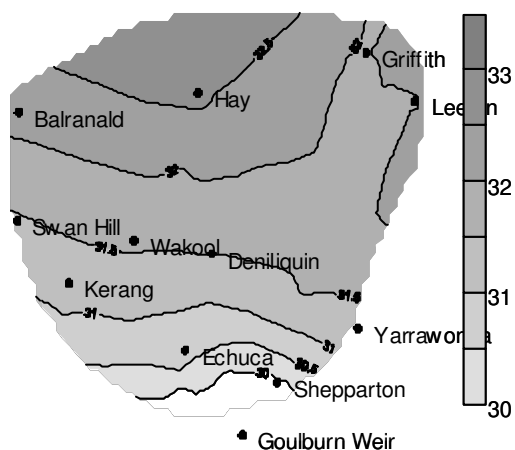
The unsaturated hydraulic conductivity function of Brook-Corey was used with the above parameters for each layer.

Appendix 2. Climate across the Riverina

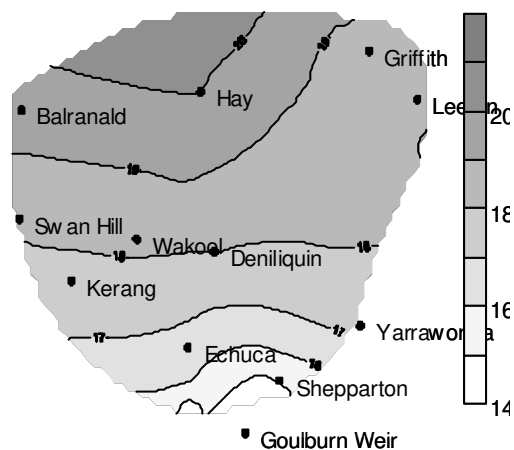
Variation in rainfall, seasonal distribution of rainfall, solar radiation, maximum temperature, VPD and pan evaporation in January throughout the Riverina. Note that the town locations are there to provide context only – the surfaces were generated from more than 500 met stations (not the dozen or so shown).



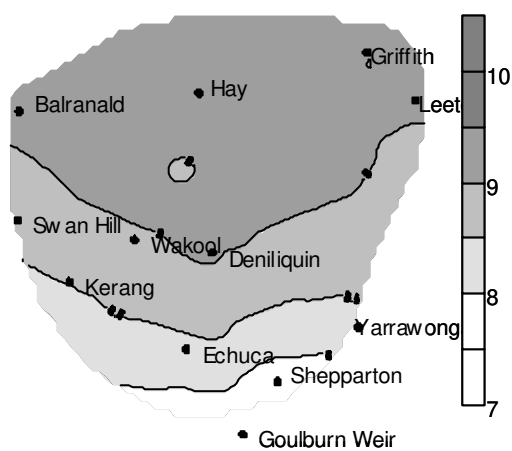
January Maximum Temperature (C)



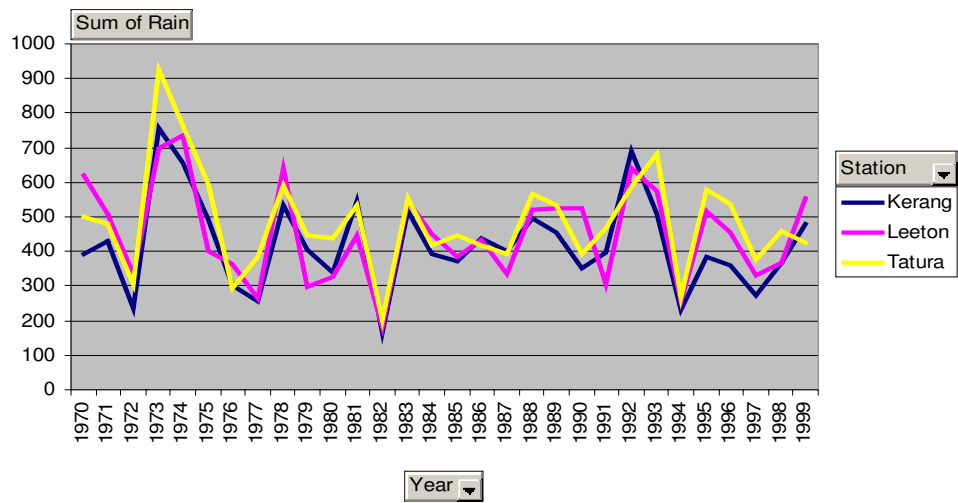
January Vapour Pressure Deficit (kPa)



January Pan Evaporation (mm /day)



Appendix 3. Rainfall variation across the Riverine Plains



Appendix 4. Soil hydraulic properties used in scenario modelling

		Topsoil	Light subsoil	Medium subsoil	Heavy subsoil
Depth		0.0 - 0.25	0.45 - 8.4	0.45 - 8.4	0.45 - 8.4
Bulk density	Mg/m ³	1.3	1.6	1.6	1.6
Residual water content	m ³ /m ³	0.02	0.05	0.05	0.05
Saturated water content	m ³ /m ³	0.35	0.35	0.35	0.35
Air entry potential	cm	-20	-20	-20	-20
"b" parameter		2.5	3	5	9
Saturated hydraulic conductivity	cm/hr	0.42	0.17	0.1	0.04
Pore interaction index		-2	-1	4	15

Appendix 5. Economic model - functions & data used

Volume & Diameter

Mean tree biomass = biomass per hectare / no.trees per hectare (outputs from APSIM)

Mean stem biomass = tree biomass * (1 - branch fraction)

Branches as fraction of total above-ground biomass = 0.25

Allometric relationships as used in 3PG:

Mean stem biomass = as * MeanDiam^{ns}

where stem coefficients are: as = 0.058; ns = 2.68

In this case, mean stem biomass is predicted by APSIM so the relationship is reversed to derive mean diameter:

Mean Diameter = (biomass / as) ^(1 / ns)

Diameter distribution functions

Ten diameter classes were formed, 5 above and 5 below the mean diameter, and the fraction of stems falling into each class was estimated from a Weibull distribution with probability density function as follows:

$$p(D) = \frac{c}{b} \left(\frac{D-a}{b} \right)^{c-1} \exp \left(- \left(\frac{D-a}{b} \right)^c \right)$$

Parameters for *E. grandis* :

a = 2.93 + 0.0011*M - 18.947/age

b = 0.438*(log(M))² - 2.388*log(M) - 0.005*age + 5.251

c = 0.209*log(M) - 0.0065*age + 1.739

where

D is tree diameter at breast height in cm.

M is the mean value of D^{2.7} for the stand

age is time in months since planting

log is natural logarithm

Source: J.Morris unpublished data and preliminary functions for eucalypts at the Trees for Profit pilot sites in northern Victoria.

Log Specifications

stump height (m) = 0.3

min.log length (m) = 3

min.small end diameter (cm) = 12

Taper function

The tree is divided into log lengths, starting from the base, and then calculates the diameter at the bottom, centre and top of each log, using the taper functions below, until it reaches the minimum acceptable diameter.

dpro = -68.46 + 67.41 * hpro - 30.2 * hpro² + 5.7* hpro³ + 69.48 * EXP(-hpro)

where dpro = diameter at a point up stem as fraction of diameter at breast height (1.3m)

hpro = height of a point up from base of tree, as fraction of top height

Source: regression for DCNR for *Pinus radiata*, Victorian average.

Log volumes

Stem volume = stem biomass / wood density

Wood Density = 475 kg/m³

Log volume in m3 = $\pi * (cd * 0.5)^2 * \log \text{length}(\text{cm}) * .0001$
 where $\pi = 3.17$; cd = centre diameter of log (cm)

Mean annual increment (MAI) = Total merchantable volume from all harvests (m3/ha) / Age (yrs)

Log stumpage values

Class	Min SED (cm)	Price \$/m3
0	12	10
1	20	22
2	25	32
3	35	45
4	45	55

Agricultural production

Benchmark agric. yield assuming irrigated clover on clay, maximum with watertable deeper than 3.25m and low salinity groundwater = 20 tonnes/ha

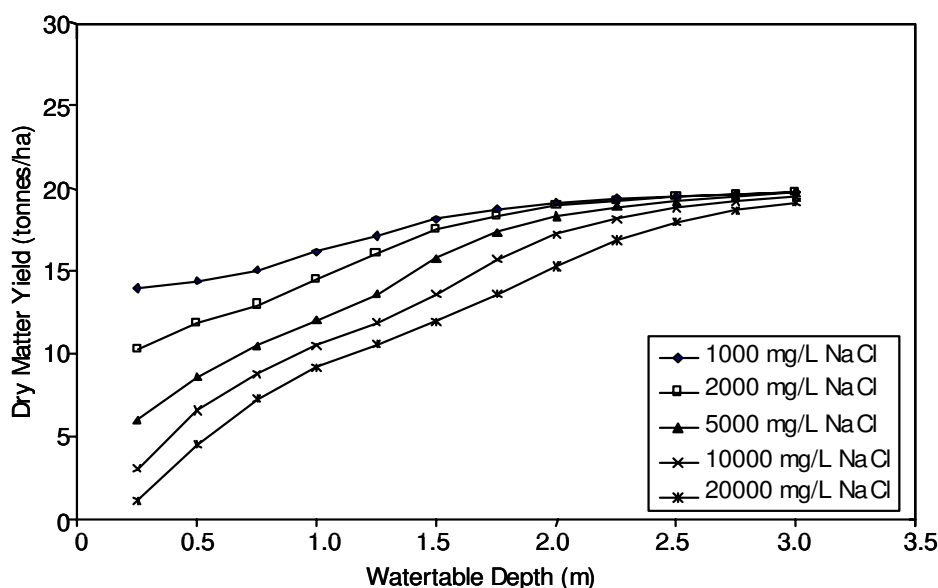
Net return from agric. crop = price net of vble cost = \$20/tonne

Benchmark irrigated ag. income = $20 * 20 = \$400/\text{ha}$.

Agric. Net return on lower-value land used for trees = $0.33 * \text{return under irrigation}$

Agricultural response to salinity

The predicted effects on agricultural productivity of varying levels of watertable depth and groundwater salinity were estimated from relationships derived from simulations by Jolly *et al* (1999)⁷, as shown in the chart below.



These relationships were converted to functional forms by regression analysis.

For the upper salinity level of 20,000 mg/L:

$$\text{minyld} = 0.0702 * \text{wtd}^3 - 1.9487 * \text{wtd}^2 + 11.816 * \text{wtd} - 1.2952$$

while at the lower salinity level of 1,000 mg/L:

$$\text{maxyld} = -0.1732 * \text{wtd}^3 + 0.2501 * \text{wtd}^2 + 3.2174 * \text{wtd} + 12.915$$

⁷Ian Jolly, Lu Zhang, Warrick Dawes and Glen Walker, "Determining "safe" watertable depths for productive irrigated crops and pastures using a soil-vegetation-atmosphere model (WAVES)", Water 1999, Brisbane

The relationship between yields for different salinities at the single depth of 0.25m was expressed as:
 $yld_{25} = -4.4647 * \text{Log}(\text{salgw}) + 13.587$

The same proportional difference between yields was assumed to hold at other depths. Hence the yield for any watertable depth could be calculated by interpolation between the upper and lower limits.

River salinity

Reduction in water export to drains & Murray (ML/ha/yr) = Vol. irrigation (mm/yr) x .01

Salinity of water used (mg/L) = Salinity of irrigation water (dS/m) x 600

Reduction in salt export (tonnes/ha/yr) = Reduction in water export (ML/ha/yr) x Salt concentrn (mg/L) x .001

Reduction in salinity at Morgan (EC/ha) = Reduction in salt export (t/ha/yr) / Salt export equiv. (6104)

Reduction in cost of river salinity (\$/yr) = Reduction in salinity at Morgan SA (EC) x cost (\$ per EC) by MDBC estimate

Cost to Murray water users per EC salinity at Morgan

Year	2000	2020	2040
Cost (\$'000/yr)	111	135	160

Source: Murray-Darling Basin Commission, based on costs of salinity to households, industry and agriculture.

Financial summaries

Net present value of stream of cash-flows (NPV) = $\sum_{i=1}^n [(B_i - C_i) / (1+r)^i]$

where B_i = benefit in year i ; C_i = costs in year i ; n = total number of years

r = discount rate = 5% per annum

Annuity (equal annual equivalent) = $r / [1 - (1+r)^{-n}] * \text{NPV}$