Interaction between trees and groundwater in the Ord River Irrigation Area


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Cover Photograph:

Description: Aerial view of African Mahogany in the Ord River Irrigation Area, Western Australia
Photographer: Dr Anthony Smith, CSIRO Land and Water
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- Paul Mock (plantation manager)
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Dr. Russell Crosbie from CSIRO Land and Water and Dr. Nico Marcar from CSIRO Sustainable Ecosystems provided review and valuable feedback on the draft report.
EXECUTIVE SUMMARY

This report describes a study of the interaction between trees and groundwater in the Ord River Irrigation Area (ORIA) in northern Australia. The research was initiated in response to growing interest in potential hydrological impacts of commercial tree planting on groundwater conditions in the irrigation area. The number of plantations of predominantly Indian sandalwood (Santalum album) has grown rapidly since the late 1990s and trees now occupy around one-quarter (3,046 hectares) of the irrigated area.

Tree plantings in the ORIA might be beneficial if they help to lower the watertable and reduce the risk of groundwater associated salinity. The perennial growth habit of trees and the deep root systems they can develop may result in less irrigation water and less rain water reaching the watertable than beneath shallow-rooted annual crops. Trees grown over a shallow watertable might also use groundwater directly, thereby assisting maintaining watertables at depth and also reducing the need for irrigation.

The principle aim of this study was to investigate the potential role of tree plantings in preventing rising watertables. This was achieved by measuring the water use of sandalwood and host plantations, and comparing the measurements to rainfall and soil moisture changes to estimate groundwater use by trees. We also analysed historical groundwater data to assess the impact of plantations on groundwater depth.

Method

Field data on groundwater levels, soil moisture content and tree water use were collected during 2006 to 2008 at three tree plantations on Ivanhoe Plain (Figure 1 and Table 1). Two monitoring sites were established within African mahogany (Khaya senegalensis) blocks at Kimberley Tree Corporation (KTC) plantation and single monitoring sites were established within sandalwood blocks at Scott Tree Farm and Mock Farm.

A simple water balance assessment was undertaken for each field site to provide estimates of rainfall, runoff, effective irrigation, canopy interception, soil evaporation and tree water use. Modelling of observed watertable decline beneath the KTC plantation provided an independent estimate of groundwater use by trees at that site.

Results

Mahogany trees at the KTC plantation have been using groundwater directly for around 10 years. Young trees probably developed tap roots into the then shallow (<2 m depth) watertable and then developed deeper root systems which followed the watertable as it fell. The aquifer beneath the KTC plantation has a low transmissivity that restricts lateral flow and movement of groundwater. Uptake of the groundwater by the trees induced a watertable drawdown beneath the plantation of 7–8 metres, substantially lower than surrounding fields. Groundwater levels have since stabilised, indicating that the groundwater uptake by the trees is now balanced by the inflow from shallower watertables in surrounding areas.

Scott Tree Farm and Mock Farm are more typical of sandalwood plantations on Ivanhoe Plain. The trees were planted over relatively deep (6–8 m depth) watertables and would have been unlikely to have access to groundwater when newly planted. Annual and daily water balances for Scott Tree Farm suggested that direct groundwater use by trees was unlikely but the results for Mock Farm suggest that although groundwater did not contribute significantly to the annual water balance it may have been used at times when soil water contents were low. The annual water balance for Mock Farm suggested that the total of annual tree water use, canopy interception and soil evaporation was approximately equivalent to rainfall and irrigation minus runoff, with no net groundwater use. However, the daily water balance indicated shorter periods of water deficit in shallow soils; at these times trees may have accessed deeper (>2 m depth) soil or groundwater.
Evapotranspiration rates were relatively low (600 to 1,000 mm yr\(^{-1}\)) in comparison to FAO56 reference evapotranspiration (1,987 mm yr\(^{-1}\)) but similar to evapotranspiration rates reported in the literature for other unirrigated woodlands in northern Australia. Evapotranspiration was low in comparison to the peak growing season rates reported for other irrigated crops in the ORIA. However, as opposed to annual crops which are not grown in the wet season, trees are active throughout the year, and our results showed that transpiration was maintained at relatively steady rates throughout the year. This indicated uptake by trees of wet season rainfall and a greater potential to use stored soil water or groundwater, dependent on the irrigation frequency and amounts.

Our estimates of groundwater uptake are subject to errors from incomplete water balance measurements; we did not directly measure irrigation amounts, runoff, soil evaporation, canopy interception or a complete annual cycle of changes in soil water content. Despite the limitations of the study, it is evident from the magnitude of tree water use at the KTC plantation in relation to rainfall and evaporation, and the historical changes in groundwater depth, that the trees use a significant quantity of groundwater annually. The extent of this groundwater use is dependent on the amount of rainfall received and irrigation water applied.

Watertable response to tree planting will vary across the irrigation area dependent on the watertable depth, local soil and aquifer properties, and management practices. Significant watertable drawdown may occur beneath trees if the underlying aquifer has low transmissivity that restricts the lateral flow and movement of groundwater in that area (e.g., Martin’s Location and Green Location). Targeted tree planting may afford a measure of control over the local watertable elevation but transpirative groundwater discharge beneath plantations may ultimately lead to accumulation of salt that could become detrimental to tree growth in the long-term, or pose a future salinity risk should the watertable rise again.

Growing trees above a shallow (2–4 m depth) watertable in areas where the underlying aquifer is more transmissive presents an alternative scenario. This could allow the trees to obtain part of their water requirement from groundwater. It is possible that this circumstance already occurs on Packsaddle Plain where the watertable elevation is maintained by the hydraulic head in Lake Kununurra and most areas are underlain by very transmissive sand and gravel beds. This situation could allow groundwater uptake by the trees to be continually replenished through induced recharge from the lake to the aquifer.

If trees are to be planted for the purpose of lowering the watertable in areas with less permeable sediments then the concept of ‘roaming’ plantations discussed by Silberstein et al. (1999) may warrant further investigation. Under this concept, tree plantations would be grown for single rotations to lower the watertable at particular sites. Following harvesting of the trees, the plantations would be replanted in new locations and other crops planted in their place. In addition to careful consideration of the salt balance, the practicality of changing between trees and annual crops and the potential economic returns from this type of management would need to be assessed.

**Recommendations**

This study has demonstrated that in suitable locations and with appropriate management, namely minimising over-irrigation, a plantation of trees can be more effective than a pump in maintaining a deep watertable and thereby controlling waterlogging and associated salinity. It is recommended that follow-on work address the economic viability of adopting such a system, and develop designs for adjacent areas under trees and crops.

We recommend further monitoring of tree water use under a range of site conditions (such as depth to groundwater, soil texture and salinity) and management (for example, planting configuration and irrigation frequency) to assess impacts on water use and growth of trees. The results of this study indicate that irrigation frequency and amounts may exceed water requirements. However, although on an annual time scale evapotranspiration may be equivalent to rainfall, seasonal imbalances may still occur between water supply and demand and if trees have not developed deep roots may not be able to access deep soil water or...
groundwater. Therefore, further work is needed on how irrigation frequency affects plant water stress, the development of deep roots and groundwater use.

In addition, the sustainability of groundwater use by trees should be investigated, in terms of how tree groundwater use might vary as plantations age, impacts on groundwater depth, and the extent of salt accumulation in the root zone and how this impacts tree growth. This could be achieved by longer term studies, or with field trials comparing tree plantings with shorter rotation crops. We recommend monitoring of the groundwater under the KTC Mahogany stand be continued to determine whether the trees have reached a steady state with their watertable. Maintaining longer term assessment of the sandalwood stands would seem warranted to determine if they explore to the watertable and perhaps lower it.

Our conclusions on the potential for tree crops to use groundwater or maintain watertables at depth in the ORIA are constrained by limitations in our methodology. We recommend that an objective of future research should be to measure all components of the water balance directly to increase the certainty around estimates of groundwater use. Alternative measurements (such as plant water potential or measurements of the stable isotope ratios in plant tissue, soil water and groundwater) may aid the assessment of tree groundwater use.

A critical factor influencing our ability to assess the older mahogany trees was a lack of understanding of the hydraulic properties of the Cununurra clay, particularly the capacity of the clay to store and yield water under different conditions (e.g., gravity drainage, preferential recharge flow, and suction induced by plant roots). We recommend detailed follow-up work to address this knowledge gap. To derive better estimates of water movement through and within the unsaturated and capillary zones, an improved understanding of the mechanisms for preferential flow and bypass flow associated with structural features in the clay (caused by swelling and shrinking) is required. This work would be particularly valuable if intensive field investigations can be undertaken.
Figure 1. Ord River Irrigation Area Stage 1
<table>
<thead>
<tr>
<th>Name</th>
<th>Aerial view at 3-km altitude</th>
<th>Site details</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTCW, KTCE</td>
<td><img src="Aerial.png" alt="Aerial view" /></td>
<td>- Managed by Kimberley Timber Corporation (KTC)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-15.6352°, 128.7714°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandalwood with mahogany (<em>Khaya senegalensis</em>) hosts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>150 trees per ha stand density</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furrow irrigated 2–3 times per dry season</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Irrigation ceased between 2001–06</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0–2 m depth to watertable when planted; 5-m average depth to watertable at KTCE and 7-m average depth to watertable at KTCW in 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stem area at breast height 14 m² ha⁻¹ in 2008</td>
</tr>
<tr>
<td>Scott Tree</td>
<td><img src="Aerial.png" alt="Aerial view" /></td>
<td>- Managed by Integrated Tree Cropping (ITC):</td>
</tr>
<tr>
<td>Farm</td>
<td></td>
<td>-15.6004°, 128.7194°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandalwood with teak (<em>Tectona grandis</em>) and <em>Cathormium umbellatum</em> hosts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900 trees per ha total stand density (including hosts)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furrow irrigated approx. monthly during dry seasons</td>
</tr>
<tr>
<td></td>
<td></td>
<td>6–8 m depth to watertable when planted; same in 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stem area at breast height 5 m² ha⁻¹ in 2008</td>
</tr>
<tr>
<td>Mock Farm</td>
<td><img src="Aerial.png" alt="Aerial view" /></td>
<td>- Managed by Paul Mock:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-15.7030°, 128.7042°</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Sandalwood with various host species including <em>Cathormium umbellatum</em>, African mahogany and various Acacia species</td>
</tr>
<tr>
<td></td>
<td></td>
<td>900 trees per ha total stand density (including hosts)</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Furrow irrigated once or twice per dry season</td>
</tr>
<tr>
<td></td>
<td></td>
<td>9-m depth to watertable when planted; 7-m depth to watertable in 2008</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Stem area at breast height 10 m² ha⁻¹ in 2008</td>
</tr>
</tbody>
</table>
1. INTRODUCTION

The Ord River Irrigation Area (ORIA) Groundwater Drainage and Discharge Evaluation project was a collaborative study by the Commonwealth Scientific and Industrial Research Organisation (CSIRO), Western Australian Department of Water (DoW), Department of Agriculture and Food Western Australian (DAFWA), Ord Irrigation Co-operative and the Western Australian and Australian Governments through the National Action Plan for Salinity and Water Quality (NAP).

The broad objectives of the study were to:

1. Assess the quality of groundwater, including salinity, major ions, nutrients and pesticide concentrations, in relation to groundwater discharge management in the Ord River Irrigation Area (ORIA);
2. Delineate and quantify groundwater discharge zones within the ORIA, including groundwater drainage to existing irrigation channels;
3. Evaluate the feasibility of using subsurface drains to control watertable rise in areas that are susceptible to waterlogging and salinity development; and
4. Evaluate the potential role of tree plantings in managing the aquifer water balance; including measurement and estimation of groundwater uptake by trees and net rates of groundwater recharge beneath them.

This report addresses the fourth objective, including the potential interactions between commercial tree plantings, groundwater level and soil salinity risk in the ORIA. It presents field data from selected sites on the Ivanhoe Irrigation Area (Figure 1) and simple water balance calculations that provide estimates of rainfall, runoff, effective irrigation, canopy interception, soil evaporation, and tree transpiration and direct groundwater uptake by trees.

The specific tasks that were undertaken in the study included:

- Review of existing tree plantings and selection of three representative field sites within the ORIA;
- Installation of groundwater monitoring wells and soil moisture sensors at these field sites,
- Installation of sap flow sensors into representative trees at the field sites; and
- Data synthesis and analysis to derive estimates of tree water use and site water balance.

The report is arranged into six main sections containing: (1) relevant contextual information for the ORIA; (2) descriptions of the field sites; (3) soil moisture investigations; (4) groundwater investigations; (5) tree water use investigations and site water balances; and (6) a synopsis of results. Conclusions and recommendation from the study are incorporated into the Executive Summary.
2. CONTEXTUAL INFORMATION

2.1. Ord River Irrigation Area (ORIA)

The Ord River Irrigation Area (Figure 1) was established during the 1960s and 1970s as part of a three-stage plan:

1. Construction of the Kununurra Diversion Dam to form Lake Kununurra; the associated works required to irrigate 10,000 hectares (ha) of land on Ivanhoe Plain; and construction of the township of Kununurra

2. Construction of the Ord River Dam to form Lake Argyle upstream of Kununurra; and the associated works and supporting infrastructure required to irrigate an additional 60,000 ha of land

3. Construction of a hydro electric power station on the Ord River Dam and the associated transmission infrastructure

Stage 1 was virtually complete by 1965. The Ord River Dam was formally opened in June 1972 but only around 2,800 ha of the additional 60,000 ha proposed for Stage 2 were developed on Packsaddle Plain. The hydro electric power station was commissioned in October 1996. Further development of the Ord Stage 2 area is subject to ongoing consideration by the Government of Western Australia and the Australian Government. A more detailed timeline is presented in Appendix A.

2.1.1. Physiography

The Ord Stage 1 area is located on the palaeo-alluvial floodplain of the lower Ord River which is bounded along its flanks by rocky ranges of outcropping sandstone and basalt. The relict floodplain extends up to 10 kilometres (km) in width across the river axis. Land elevation varies by only around 10 m within the irrigation area whereas the surrounding ranges rise 300 m to 400 m above the plain.

Packsaddle irrigation area is located on Packsaddle Plain to the south and west of Lake Kununurra, which is held by the Kununurra Diversion Dam. The southern and eastern sides of Packsaddle Plain are bounded by the Carr Boyd Ranges. Ivanhoe Irrigation area is located on Ivanhoe Plain to the north of Lake Kununurra and between the east bank of the Ord River and the western edge of the Pincombe Range. Ivanhoe Plain extends into Martin’s Location, Green Location and Cave Spring Gap.

The township of Kununurra is located approximately 30 km west of the Northern Territory border and around 100 km from the north coast of Western Australia. In a straight line, it is more than 2,000 km from Perth (>3,000 km by road) and approximately 400 km from Darwin (>800 km by road).

2.1.2. Climate

The Ord River region has a wet-dry tropical climate characterised by well-defined wet and dry seasons. Approximately ninety percent (90%) of the annual precipitation falls during the wet season between mid-November and March. The average July to June rainfall at Kununurra Airport from 1960–61 to 2007–08 was 796 millimetre per year (mm yr\(^{-1}\)), although there was significant variation between years (Figure 2). During this period, the maximum July to June rainfall was 1,476 mm in 1999–00 and the minimum was 366 mm in 1969–70.

Following the 1976–77 wet season the ORIA experienced a sixteen-year period of below average rainfall, which was 15% below the long-term average (Table 2). During the recent wet period from 1998–99 to 2001–02 the total rainfall was 45% greater than the long-term average.

Air temperatures are typically high to very high throughout the year. July is the coolest month, with mean daily maxima and minima of 31 degree Celsius (°C) and 14 °C, respectively. November is the hottest month, with mean daily maxima and minima of 39 °C and 25 °C. Average annual pan evaporation for 1960 to 2007 was around 2,760 mm yr\(^{-1}\);
greater than three times rainfall. Average monthly pan evaporation exceeds average monthly rainfall in all months except February.

2.1.3. Irrigation and drainage

Around 12,000 ha of irrigable land within the Packsaddle and Ivanhoe irrigation areas is serviced by approximately 134 km of clay-lined supply channels and 155 km of unlined surface drains. Downstream of Lake Kununurra on Ivanhoe Plain, the irrigation supply channel system diverts water from Lake Kununurra, through the irrigation area and back into the lower Ord River at various drainage and relief points below the dam. On Packsaddle Plain, which is directly upstream of the diversion dam, lake water is raised by pumping into the supply channel system and the return water flows into the Dunham River via Packsaddle Creek or directly back into Lake Kununurra via irrigation drains.

![Figure 2. Annual July to June rainfall at Kununurra Airport](image)

**Table 2. Average annual rainfall at Kununurra Airport for various periods**

<table>
<thead>
<tr>
<th>Wet seasons</th>
<th>Period, yr</th>
<th>Average-annual rainfall, mm yr⁻¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>1960–61 to 2007–08</td>
<td>48</td>
<td>796</td>
</tr>
<tr>
<td>1976–77 to 1991–92</td>
<td>16</td>
<td>673</td>
</tr>
<tr>
<td>1998–99 to 2001–02</td>
<td>4</td>
<td>1,154</td>
</tr>
</tbody>
</table>
2.1.4. Groundwater

Groundwater exists in the alluvium and bedrock throughout the Ord River region. It is used for public and private potable water supply in the Stage 1 area and is a minor supply for irrigation in areas outside of the channel system. The groundwater quality is variable and can be unsuitable for both drinking and irrigation (Smith et al. 2007).

The palaeo-Ord valley is filled by a complex, aggraded sequence of fluvial sediments that were generally deposited on the palaeo-topographic surface as a sequence of upward-fining gravel, sand, silt and clay (O'Boy et al. 2001, Lawrie et al. 2006). At the valley-scale, these sediments broadly constitute four unconfined aquifer units consisting of: (1) basal sand and gravel palaeochannel sediments with moderate to very high permeability; (2) overlying sand with moderate permeability; (3) silt, sandy-silt and silty-sand with low permeability, and (4) upper clay and silt with low permeability. In Figure 3, the upper clay, silt and sandy-silt layers are combined.

The watertable cross sections presented in Figure 4 depict the contemporary watertable elevation as well as the earliest known water level recording for each piezometer—which is generally also the minimum recorded water level—and the maximum known water level recording.

The watertable underlying the irrigation area was relatively deep prior to agricultural development in the early 1960s and it is likely that groundwater was replenished mostly by seasonal surface-water infiltration when the Ord River was flowing and during inundation events. Direct groundwater replenishment from rainfall was probably very small because the watertable was deep and the soil profile could absorb and store seasonal rainfall without significant deep drainage.

During the past forty years the watertable has risen by 10–20 m beneath most of the irrigation area due to hydrological impacts of agricultural development (Figure 5). The direction of subsurface drainage is now mainly toward the Ord River, Lake Kununurra, Packsaddle Creek and other surface water drains. More recently, the watertable beneath northern Ivanhoe Plain intercepted the deepest irrigation drains, which are helping to prevent further groundwater rise.
Figure 3. Interpreted distributions of aquifer units (Smith 2008)
(a) Basal sand and gravel, (b) intermediate sand, (c) upper clay and silt
Figure 4. Watertable cross sections (Smith 2008)
Section lines are marked on Figure 3: (a) Packsaddle Plain, (b) central and northern Ivanhoe Plain, (c) northern Ivanhoe Plain and Cave Spring Gap
Figure 5. Estimated depth to watertable in 2005–06 (Smith et al. 2009)
2.1.5. Salinity

Annual pan evaporation in the ORIA exceeds annual rainfall by a factor greater than three. Ali et al. (2003) determined that soil salinisation can occur if the watertable is less than approximately two metres below the ground surface for an extended period. Soluble salts in shallow groundwater can be concentrated at the soil surface by groundwater evaporation, which ultimately leads to salinisation if ‘wash-off’ of the surface salt and leaching of subsurface salt are incomplete.

Groundwater quality in the ORIA was reviewed by Smith et al. (2007) and soil salinity in the Ord region was reviewed by Smith and Price (2009). A brief overview of surface-water and groundwater salinity information from those reports is presented below; additional detail can be found in the reports.

Surface water from Lake Argyle is fresh with electrical conductivity (EC) of around 0.2–0.3 millisiemen per centimetre (mS cm⁻¹). Environmental waters can be classified hydrogeochemically on the basis of the cation and anion species mix (Fetter, 1994, Figure 10.9; following Piper, 1944). Regionally, surface waters are bicarbonate type in anion composition but tend to have no dominant cation type. This is likely to reflect geochemical interaction between rain water and the regolith and rock of the surface catchments. Evaporation, transpiration and subsurface geochemical interactions give rise to a range of groundwater geochemistry and salinity. Groundwater beneath the ORIA can be bicarbonate type, chloride type or non-dominant in anion composition, and is generally sodium type or non-dominant in cation composition. Although limited data are available, the salinities of surface water, soil water and groundwater are strongly correlated with chloride ion concentration (Figure 6) and it is expected that sodium chloride will normally be the dominant salt associated with salinisation.

Based on USDA (1954) irrigation salinity classes, groundwater in the ORIA is mostly medium salinity (0.25–7.5 mS cm⁻¹) though measurements vary from low salinity (< 0.25 mS cm⁻¹) to very high salinity (> 22.5 mS cm⁻¹). A statistical summary of groundwater EC measurements collected in the ORIA since 1982 is presented in Figure 7. In general there is no indication of either an increasing or decreasing trend in groundwater salinity during that time. Based on USDA (1953) salinity classes, and Sodium Adsorption Ratio (SAR) hazard classes, groundwater in the ORIA generally poses a medium-to-low hazard to soil structure.
Areas of shallow groundwater have now persisted within the ORIA for the past decade and there are several localised examples of secondary salinisation (Smith and Price 2009). To date, most of the farmland within the irrigated area is unaffected by salinity and the risk of future salinisation is mostly restricted to areas around the margins of the valley with poorly draining clay soil. Analysis of groundwater controls and salinity risk in the ORIA based on past watertable rise and predictions of future groundwater elevation is considered in more detail by Smith et al. (2006a) and Smith (2008).

Figure 7. ORIA groundwater salinity measurements 1982 to 2006
Statistical summary (adapted from Smith et al. 2006)
2.1.6. Cropping history and commercial tree planting

The Ord Stage 1 area was set up as a cotton monoculture during the early 1960s (Appendix A). Its success was rapid but relatively short lived. In the 1966–67 growing season the Ivanhoe irrigation area produced twenty percent of Australia's cotton crop (Commonwealth of Australia 1979) but during the following 10 years the industry was devastated by pest problems and by 1975 cotton growing had effectively ceased.

Experimental areas of rice paddies were cultivated on Ivanhoe Plain from 1974 to 1982 but this concept also was abandoned due in part to the large leakage rates from the paddies and the associated increases in groundwater rise beneath them (Laws and George 1984). Profitable agricultural enterprise was re-established during the 1980s through crop diversification, growing of improved varieties and better pest management. Between 1982 and 1998 the value of agricultural production in the ORIA increased from less than AU$5 million per year to greater than AU$50 million per year (Greiner and Johnson 2000).

During the period 1990 to 1999 the area under active cropping (Figure 8) increased from 4,300 ha to 11,000 ha, mainly through the introduction of sugar cane. In the 2002–03 growing season, crop contributions to the total value of agricultural production were: horticulture 49%, sugar 34%, hybrid seeds 8% and field crops 5%.

Figure 8. Cropped area 1964–65 to 2006–07

Less than five years later in 2007, the sugar mill at Kununurra was closed due to a combination of factors that included a decline in the annual production of sugar cane, the introduction of tree plantations in place of sugar cane and ongoing uncertainty about the future development of the proposed 1Ord Stage 2 area. The sugar cane crop was not re-planted in the 2007–08 growing season.

Commercial plantings of Indian sandalwood (Santalum album) were first introduced in the ORIA during the late 1990s, although the WA Department of Agriculture had been trialling experimental plots at the Frank Wise Research Institute on Ivanhoe Plain since the early 1980s (Bristow 2004). Done et al. (2004) reported that approximately 1,000 ha of Indian sandalwood had been planted between 1999 and 2004, and that the planting was progressing at around 100 ha per year. This now appears to be an underestimate.

The survey conducted for this study in 2006 (Price A and Janke S, Ord Irrigation Cooperative, pers. Comm., June 2006) indicated that approximately 2,300 ha of sandalwood had been planted at that time, which would represent a planting rate of 400–600 ha per year.

1 Approximately ninety percent (29,000 ha) of the Ord Stage 2 area in Western Australia was proposed to be planted with sugar cane (Kinhill Pty. Ltd. 2000)
since 2004. An additional 1,500 ha of crop land had been bought or leased for the purpose of establishing tree plantations in the near future. The survey data are presented in Figure 9, which includes smaller areas of mangoes (approx. 700 ha) and citrus (approx. 20 ha).

Figure 8 depicts more recent data from the Department of Agriculture and Food Western Australia (DAFWA) (Bright F, DAFWA, pers. comm., January 2009). In 2006–07 the planted area of sandalwood was estimated to be 3,046 ha, which was approximately 24 percent of the total cropped area.

Sandalwood is a hemiparasite and requires a host species to provide water and nutrients. Seedlings are planted together with their pot host and intermediate (3–5 years) or long-term (up to 15 years) hosts. The commercial rotation period is anticipated to be approximately 15 years and therefore the first harvests from the ORIA are not expected until around 2015, or later. Soil moisture probes have been tried for irrigation scheduling but the most common method for determining when irrigation is required is based on the time since last irrigation and visual inspection of water stress in the host trees. The growing methods are developing rapidly but they are still largely experimental. There is a tendency to over irrigate rather than under irrigate because of uncertainty about the water requirement of trees and the potential financial consequence of trees dying. On the other hand, over watering and waterlogging can lead to other problems such as fungal diseases (Jurskis 2005).

2.2. Groundwater use by trees in irrigated areas of Australia

Water contained in the saturated part of the soil profile is known as groundwater and the upper surface of the zone of saturation is commonly referred to as the watertable. The level of the watertable is indicated by the surface of water in an open well drilled to the saturated zone. Groundwater is easily recognised because it will flow into an open hole that is dug below the watertable. In contrast, soil water contained in the unsaturated part of the soil profile between the watertable and the ground surface will not flow into an open hole because the water pressure is less than atmospheric pressure. The unsaturated part of the soil profile contains water from rainfall or irrigation, and there is a layer of soil above the watertable that is kept moist by capillary rise of water, called the capillary fringe (part of the capillary fringe may also be saturated). Global reviews of plant rooting distributions have shown that the majority of root biomass occurs in the top 50 cm of the soil profile (Cannadell et al. 1996; Jackson et al. 1996); therefore, plants typically obtain most of their water from shallow soil. However it is well established that plants have the capacity to explore soil profiles to much greater depths, and if surface soil water supply is limited or unreliable plants may rely on groundwater. Groundwater uptake may occur from the unsaturated part of the capillary fringe, where soil is oxygenated, or tree roots have also been found below the level of the watertable in anoxic soil (Stirzaker 2002).

Investigations in other parts of Australia have found that trees can use significant amounts of groundwater (Mensforth et al. 1994, George et al. 1999, Silberstein et al. 1999, White et al. 2002, Ayars et al. 2005, Benyon et al. 2006, Eamus and Froend 2006, O’Grady et al. 2006a). Groundwater use by trees can be seen as undesirable in areas where the groundwater resource is in demand for other uses (Zencich et al. 2002, Benyon et al. 2006). It can be seen as beneficial in areas where the watertable is rising and shallow groundwater is causing or threatening to cause land degradation (White et al. 2002, Wildy et al. 2004). The rate of groundwater uptake by trees depends on the species, rainfall, watertable depth, groundwater quality and soil texture (Benyon et al. 2006, Polglase et al. 2002).

Tree planting for watertable and salinity control has been proposed in dryland salt-affected areas of Australia (Stirzaker et al. 2002). The projected benefits of tree planting in irrigation areas include reducing groundwater recharge, lowering watertables, re-using drainage water, rehabilitating saline soil, providing windbreaks, producing fodder and improving the environment (Driver 1992). In particular, profitable timber production leading to a lowered watertable has been proposed for irrigation areas in southeast Australia. Though examples are known where tree plantings have significantly lowered the watertable beneath them, salt management has been identified as a potential problem over longer time scales because trees remove water by transpiration and leave behind salt in the rootzone (Heuperman 1999,
Silberstein et al. 1999, Vertessy et al. 2002). The concentration of salts in the rootzone depend on the position of trees in the landscape, transpiration rates, initial soil and groundwater salinity, groundwater depth, leaching by rainfall and the extent of lateral subsurface water flow (Marcar and Morris 2005).

Groundwater uptake may be important to vegetation in environments with a seasonal rainfall distribution, by allowing continued transpiration and growth during the dry season (O’Grady et al. 2006b). Irrigated vegetation also can use groundwater. For example, Polglase et al. (2002) found that trees irrigated once or twice a year in the Murray-Darling Basin used significant amounts of groundwater at 3 m depth and could assist in controlling rising watertables. The rate of groundwater use can be influenced by the irrigation frequency because trees are less likely to increase root growth towards the watertable if the surface soil is constantly moist and the soil water is not limiting.
Figure 9. Tree plantings in the ORIA at June 2006
3. DESCRIPTION OF THE FIELD SITES

We chose three study sites in some of the oldest plantations within the ORIA to maximise the likelihood that tree roots would have grown to the depth of the watertable and were using groundwater. We also chose sites where trees appeared to be healthy. Anecdotal evidence initially suggested that our sites covered a range of groundwater depths, although subsequent drilling showed that groundwater depth was similar at all sites (Table 1).

3.1. KTC mahogany plantation

The Mahogany-sandalwood plantation located along Arawodi Road (Figure 10) is currently managed by the Kimberley Timber Corporation (KTC) primarily for the mahogany timber. African mahogany (*Khaya senegalensis*) was planted as the host species for the sandalwood (*Santalum album*) when the plantation was established under different management in 1997. This plantation was the first commercial tree-growing venture in the ORIA (Done *et al.* 2004).

For a number of reasons the production of sandalwood with Mahogany hosts proved to be unsuccessful and the plantation was put under minimal management from 2000 to 2006. During that time the trees were not irrigated but the mahogany grew rapidly and eventually shaded the sandalwood, which did not grow well. After KTC took over management of the plantation in 2005 irrigation recommenced and has occurred at a frequency of two to three...
times per dry season since then. As for the other sites in this study, the amount of water applied during irrigation has not been measured. During this study we measured the changes in soil water content following irrigation events (see details below) and found that on average approximately 50 mm of water enters the soil profile. The stocking density of mahogany trees is approximately 150 trees per ha.

The site was selected for this study because of the intense interest in the changes in the watertable beneath the trees and prior anecdotal evidence that it had drawn down significantly after trees were planted. In particular, there was a perception that similar watertable control might be achieved at other locations by planting trees there, or that similar drawdown of the groundwater level could be expected at other locations where trees were already planted.

The two sites within the mahogany blocks that were selected for this study are indicated in Figure 10. The most western site (denoted KTCW) was within the part of the plantation where tree growth has been more vigorous and the canopy density is largest. The eastern site (denoted KTCE) was within the part of the plantation where tree health and growth appear to be limited by an unfavourable change in site biophysical conditions, such as a change in soil depth, texture or chemistry. The distinct transition between the two zones that is evident in the photos in Figure 10 does not correspond to the geometry of the irrigation bays and is unlikely to be caused by irrigation practices. Additional time-series satellite images from 1972 to 2008 are presented in Appendix B.

3.2. Scott Tree Farm

ITC’s Scott Tree Farm is located along Research Station Road on northern Ivanhoe Plain. The field site was selected within a healthy block of *S. album* that was planted in 2001 (Figure 11). The oldest sandalwood blocks on the farm were planted in 1999 (Appendix E) but the health of those trees was considered to be inferior and unfavourable for the study.

Within the block selected for the study, the sandalwood grows in alternate rows with teak (*Tectona grandis*) and *Cathormium umbellatum* as the host species. The total stand density of sandalwood and host trees is approximately 900 trees per ha and they are irrigated approximately monthly during dry seasons.

The depth of groundwater below the ground surface increases from east to west across the site toward the Ord River, and is approximately 7–8 m below the ground surface at the monitoring location indicated on Figure 11. Additional time-series satellite images from 1972 to 2008 are presented in Appendix C.

Figure 11. Images of Scott Tree Farm
(a) Aerial view showing the location of sap flow and soil moisture monitoring equipment, (b) sandalwood trees and hosts
3.3. Mock Farm sandalwood

The sandalwood block at Mock Farm was planted in 2000 and is growing in alternate rows with various host species including *Cathormium umbellatum*, African mahogany and various *Acacia* species (Figure 12). These trees were selected for the study because they are healthy, relatively old for the irrigation area and are only irrigated once or twice throughout the dry season. The total stand density including the sandalwood and host trees is approximately 900 trees per ha.

The depth to groundwater increases in a north-westerly direction across the site toward the Ord River and is around 7 m below the ground surface beneath the sandalwood block. Additional time-series satellite images from 1972 to 2008 are presented in Appendix D.

Figure 12. Images of Mock Farm sandalwood block
(a) Aerial view showing the location of sap flow and soil moisture monitoring equipment, (b) sandalwood trees and hosts
4. SOIL MOISTURE INVESTIGATION

4.1. Methods

4.1.1. Field installation and data logging

At each field site, MP406 capacitance probes were installed to measure soil moisture at five depths (30, 50, 100, 150 and 200 cm) below the soil surface. The sensors were positioned in a row aligned with the direction of the irrigation furrows approximately 1.5 m apart and directly adjacent to the trees being monitored for water use by sap flow equipment. Thus, the probes were not vertically aligned. This was deliberately set up to avoid water flowing down a tube beyond each sensor to the next one, artificially increasing the soil water content around the sensor.

We installed the probes according to the manufacturer’s recommendations. To install each soil moisture probe, a soil core of required depth was first removed using a hydraulic ram and the probe was then lowered into the hole and pushed firmly into the undisturbed soil at the base of the hole using a rigid piece of tubing. The hole above the probe was then backfilled with bentonite (Benseal) to minimise preferential percolation.

At each site the five sensors were connected to an automatic data logger, which recorded the soil moisture content every 30 minutes. This amounted to 240 measurements (5 x 48) per day at each site. The data were collected for a 278-day period (3/8/2007 to 7/5/2008) which encompassed the mid-to-latter part of the 2007 dry season and the 2007–08 wet season.

4.1.2. Calibration of the soil moisture probes

Each MP406 soil moisture probe was calibrated in the laboratory using equilibrated mixtures of water and re-packed Cununurra clay from soil cores (Smith et al. 2006b) to achieve five known soil moisture levels equivalent to 4.5%, 10.3%, 16.3%, 24.9% and 30.8% gravimetric water content. A second-order polynomial was fitted to the laboratory data for each probe and the field measurements were converted to gravimetric soil moisture content using those models. An example is presented in Appendix F.

4.1.3. Soil moisture calculations

Gravimetric soil-water contents measured by the soil moisture probes were converted to volumetric soil-water contents using the following relation:

$$\theta_v = \theta_g \times \frac{\rho_b}{\rho_w}$$

where $\theta_v$ is the volumetric water content of the soil, $\theta_g$ is the gravimetric water content of the soil, $\rho_v$ is the density of the soil water and $\rho_b$ is the soil bulk density. The conversion from gravimetric to volumetric water content was required to estimate the total amount of water stored in different parts of the soil profile. For clay with porosity 0.5–0.6 and soil grains (rock) with density 2.65 g cm$^{-3}$ the soil bulk density is in the range 1.06–1.3 g cm$^{-3}$. In this study we adopted a mid-value in this range of $\rho_b = 1.1$ g cm$^{-3}$. In comparison, Bridge and Muchow (1982) determined bulk density measurements in Cununurra clay of around 1.35 g cm$^{-3}$ under cultivated fallow, and around 1.4 g cm$^{-3}$ under cropping.

We multiplied soil water content measured by each sensor by the depth of the soil layer between each sensor as

$$V = D \theta_v$$

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3 Soil core samples collected from the ORIA during the piezometer drilling program in September 2006 (Smith et al. 2006)
where \( V \) is the volume of water stored within the effective depth \( D \). We then added these values to get total water stored in the 2 m profile. So, for example, we assigned the soil water content measured by the 30 cm depth probe to the soil layer from 0 to 40 cm, the value from the 50 cm probe to the layer from 40 to 75 cm, the value from the 100 cm probe to the 75 to 125 cm layer and so on until the final probe at 200 cm depth. There may have been variation within each of these soil layers that we did not capture, but the sampling depths were chosen based on the number of soil moisture probes we had to sample across all sites.

4.2. Results and discussion

4.2.1. General observations

Figure 13 depicts soil moisture content changes over time at the three sites in this study. In each plot the vertical axis represents depth below ground surface and the horizontal axis represents the progression of time in days. Day zero corresponds to 3rd August 2007 and day 278 (final day) corresponds to 7th May 2008. Gravimetric soil moisture was contoured at 2-percent intervals with blue tones representing wet soil and orange tones representing relatively drier soil. Rainfall and irrigation events are indicated along the upper boundary of each plot, which represents the soil at 30 cm depth below the ground surface (i.e., the depth of the shallowest soil moisture sensor at each site). The moisture content of surface soil that is directly exposed to the atmosphere is expected to be considerably less than at 30 cm depth except during irrigation and rainfall events.

Triangle and diamond symbols plotted along the top axis of each plot represent the timing of rainfall and irrigation events. The triangles are scaled in size by the daily-rainfall amount with the largest triangle corresponding to the maximum rainfall of 118 mm on 28th February 2008. The diamonds symbolise the timing of irrigation events but they are not scaled by the irrigation amount, which was unknown.

The following general observations were apparent from Figure 13, and further analysis is provided in subsequent sections.

- Soil moisture generally decreased with depth and was typically 14–16% (gravimetric) at 200 cm depth.
- Below 150 cm the soil moisture content was relatively stable, except at KTCE where deep drainage below 200 cm depth was evident during the 2007–08 wet season (day 160 onward). This deeper penetration may have been due to the apparently lower leaf area index in the eastern part of the stand.
- Soil moisture content was variable in response to rainfall and irrigation to a depth of around 100 cm and typically varied in the range 16–25%.
- Soil at Mock Farm was comparatively drier during the irrigation season but only a limited dataset was obtained due to an undetermined fault with the field installation of sensors — the fault appeared to occur when the soil moisture was less than around 12%.
- At Scott Tree Farm soil moisture dried out in the top 80 cm or so prior (Day 120 on) to the wet season indicating likely uptake by roots and/or evaporation. During the wet season the surface soil was always moist, indicating that rainfall was greater than combined evaporation and tree uptake.
- Overall, the soil moisture values measured in this study were consistent with other measurements of soil moisture in Cununurra clay (see Appendix G).

4.2.2. KTC mahogany plantation

Figure 14 and Figure 15 present time-series plots of the measured gravimetric moisture content at each depth at KTCE and KTCW; the same data were used to produce Figure 13. Relatively dry soil was present at 200 cm depth at both sites, with moisture content reducing from around 20% at 150 cm to 14% at 200 cm. This pattern was consistent with the moisture content of soil-cores collected during piezometer installation (Appendix H) which decreased...
with depth to a minimum of less than 10%. This indicates that rainfall and irrigation wet the surface soil only and are subsequently transpired or evaporated, with little water penetrating to deeper soil layers. Soil removed during piezometer installation was dry until near to the watertable (6 to 7 m), when soil moisture content increased (Appendix H, CO39 and CO40).

At KTCE the soil moisture content at 100 cm depth was often greater and more variable than at 50 cm, particularly between January and March 2008. The bottom panel of Figure 13 also shows the penetration of a wetting front (in blue) passing 200 cm. As soil moisture usually increases with depth, these data suggest that there may have been rapid drainage of water along preferential flow paths, for example a deep crack in the clay. This component of the drainage would not be detected by the soil moisture probes above that depth if the probes were not located within the preferential flow area and there was insufficient time for significant absorption into the surrounding soil matrix. In addition, because the individual sensors were not vertically aligned they do not represent a vertical drainage profile, and so may characterise lateral as well as vertical variation in soil moisture.

At KTCW there were generally lower soil moisture contents than at KTCE, and during the wet season there was a more consistent decrease in moisture content with depth. There may also have been less penetration of water to depth at KTCW than at KTCE because of the larger trees and apparent higher leaf area index (we did not measure this, but it was clear from observation) which would have resulted in greater canopy interception of rainfall.

Following the end of the wet season there was rapid depletion of soil water down to 130 cm at KTCW. Unfortunately, the failure of the instruments at KTCE at the end of the wet season means that we cannot compare the two sites during this period. However, prior to this, wetting and subsequent drying of the top 100 cm of soil is evident following irrigation or rainfall events at both KTCE and KTCW, but is more pronounced at KTCW. This indicated that water was transpired or evaporated quickly after irrigation and rainfall events. Soil evaporation at KTCW would have been lower than at KTCE due to the closed canopy and shady conditions, so the drier soil was likely the result of greater rates of tree transpiration and canopy interception.

It is not known why the soil water content in the top 50 cm of soil at KTCW was so high and remained so stable at the beginning of the monitoring period. As this was the dry season and there were no rainfall or irrigation events, a decrease in soil water content over time would be expected, as seen for example at Mock Farm (Figure 16). Therefore it is possible there was error in soil measurement measurements during this time.

We calculated the amount of water added to the soil profile during discrete rainfall or irrigation events at KTCE and KTCW from the changes in soil moisture (Table 3 and Table 4). The event dates in each table correspond to the times at which soil moisture began to increase at that site; as sensed by the soil-moisture probe at 30 cm depth. The event dates therefore vary according to the timing of irrigation and rainfall at each site and the time required for infiltration and moisture changed at the probe depth. In particular, daily rainfall amounts measured at the three main rainfall stations in the ORIA can vary significant due to spatial variation of local rainfall distribution. We use these values later to estimate the amount of water added to the soil profile following irrigation events, and for comparison of the apparent effective rainfall with our estimates of canopy interception and runoff.

4.2.3. Scott Tree Farm and Mock Farm

Plots of gravimetric water content at each depth at Mock Farm and Scott Tree Farm are depicted in Figure 16 and Figure 17. The soil moisture sensors stopped working at Scott Tree Farm during February and March 2008 and only a short series of measurements was acquired at Mock Farm. Despite the gaps in measurements, it was evident that soil moisture content was not affected by rainfall and irrigation below 150 cm—moisture contents generally decreased with depth below this level. Hence, similar to the KTC plantation, it appears that there was little water penetrating to deeper soil layers. Also similar to the KTC plantation, there was soil water depletion in the top 100 cm at Scott Tree Farm. Contrary to expectations, the soil moisture content was higher during the dry season than during the wet season at Scott Tree Farm. This reflects the higher frequency of flood irrigation events at this
site (approximately monthly) than at the other sites. In contrast, Mock Farm, with the lowest irrigation frequency, had the lowest soil moisture content of all sites (at least during the limited measurement time during the dry season). The low soil moisture at Mock Farm also likely reflects a relatively high rate of tree water use (see results following). Estimates of the amount of water added to the soil during rainfall and irrigation events at Mock Farm and Scott Tree Farm sites are presented in Table 5 and Table 6.

Figure 13. Soil moisture change with time at the three field sites
Gravimetric soil moisture content is contoured in space and time at 2-percent intervals; triangle symbols represent daily rainfall scaled by the daily rainfall amount; diamond symbols represent known irrigation events; day 0 is the 3/8/2007 and day 278 is 7/5/2008.
Figure 14. Soil moisture content at five different depths at KTCE

Table 3. Estimation of change of soil water storage at KTCE
Events are labelled on Figure 14

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Figure 15. Soil moisture content at five different depths at KTCW

Table 4. Estimation of change of soil water storage at KTCW
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Figure 16. Soil moisture content at five different depths at Mock Farm

Events are labelled on Figure 16

Table 5. Estimation of change of soil water storage at Mock Farm
Events are labelled on Figure 16

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5. GROUNDWATER INVESTIGATION

5.1. Methods

5.1.1. Piezometer installation

A series of piezometers were installed at each of the field sites in September 2006 to complement the existing network of groundwater monitoring wells within the irrigation area. Descriptions of the drilling, lithology logs and piezometer constructions are presented in a separate drilling report (Smith et al. 2006b). Each piezometer was equipped with an Odyssey Capacitance Water Level Logger, which was programmed to record the water level every one or two hours. The reported measurement sensitivity of the Odyssey instrumentation is approximately 0.8 mm (Dataflow Systems, Christchurch, New Zealand), although in practice the sensitivity may be less than this. All water level data collected during the study were archived in the Western Australian state water resources (WIN) database.

5.1.2. Watertable elevation

Watertable potentiometric contours were developed for each site using groundwater elevation data collected for the study and supplementary data from other groundwater monitoring programs. Associated cross sections of the watertable were also analysed for evidence of variation in groundwater recharge variation beneath the plantations.

5.1.3. Groundwater modelling

An existing groundwater flow model of the ORIA Stage 1 area developed by Smith et al. (2006a) was used to derive an estimate of groundwater use by trees at KTC plantation based on observed watertable drawdown beneath the plantation. The Ord Stage 1 groundwater flow model was developed and implemented in the simulation system FEFLOW for the purpose of exploring land and water management options to control rising groundwater and salinisation risk within the Stage 1 area. It simulates lateral and vertical groundwater flow and predicts the groundwater elevation and depth to watertable beneath Packsaddle and Ivanhoe Plains. The model does not simulate the salt balance or salt concentration in groundwater. Calibrated aquifer properties in the region of KTC plantation were, as follows: effective porosity 0.2, horizontal hydraulic conductivity 1 m d⁻¹ and vertical hydraulic conductivity 0.1 m d⁻¹.

5.1.4. Spectral analysis

Evidence of daily and sub-daily variation in watertable elevation was explored using spectral analysis. Response spectra were determined using the Fast Fourier Transform (FFT) and FFT filtering tools as implemented in the software package OriginLab. The term Fourier analysis refers to any data analysis technique that describes or measures fluctuations in a time series by comparing them with sinusoids. Well-known methods include filtering, least squares regression on sinusoids, and harmonic analysis (Bloomfield 1976; Chatfield 1975; James 1995). Fourier techniques are commonly used to detect frequency components that are hidden within a 'noisy' signal.

The discrete FFT is a computationally efficient algorithm that enables regularly sampled time series data to be fitted by a set of harmonic frequencies. For a time series of n data values, the FFT fits n/2 frequencies over the frequency range 2v_N/n ≤ v ≤ v_N, where v_N = 1/2Δt is known as the Nyquist frequency, and Δt is the sampling interval. The Nyquist condition simply states that the largest frequency (i.e., smallest period) that can be reasonably fitted to the data is equal to twice the sampling interval. This corresponds to fitting, at most, one local maxima or minima between each pair of data point in the time series. From a practical point of view, the Nyquist conditions tells us that it is unreasonable to fit, say, a semi-diurnal frequency (12 hour period) to data that has only been sampled 24 hourly. The smallest

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4 http://www.odysseydatarecording.com/
5 Finite Element subsurface FLOW system (DHI-WASY GmbH)
6 Origin 7 SR4 v7.0522(B552) http://www.OriginLab.com
period or highest frequency that should be fitted to diurnal data is 48 hours or 0.5 cycles per day. The FFT is appropriate for time series with a total number of values equal to $2^m$, where $m$ is an integer value.

In this study, FFT analyses were performed on selected hydrometric time-series records of 1024 ($2^{10}$) or 512 ($2^9$) consecutive water level values with either 2-hr (0.0833-d) or 1-hr (0.0417-d) measurement intervals. Missing water level records in the times series were filled by linear interpolation prior to the analyses. A cut-off frequency of 0.667 per day (i.e., period 1.5 d) was selected for the FFT low-pass and high-pass filters.

5.2. Results and discussion

5.2.1. Watertable analysis

KTC mahogany plantation

Contemporary groundwater elevation beneath the KTC plantation is depicted in Figure 18 and corresponding watertable cross sections are depicted in Figure 19. The cross-sections illustrate both the contemporary watertable elevation and the watertable elevation in the late 1990s when the mahogany trees were planted. The historical minimum and maximum water level elevations measured in each piezometer also are indicated for piezometers with long-term records.

In 1965 the watertable beneath the plantation was approximately 20 m below the ground surface. By 1984 it has risen to 8–10 m below the surface and by the late 1990s had almost reached the ground surface. The proximity of the watertable to the ground surface indicates that the soil surface would have been prone to waterlogging, particularly in the wet season. Indeed, there have been reports of the watertable being very near the surface in 2000-2001 (Fay Lewis, personal communication, 2007). The mahogany trees were planted as host trees to sandalwood in 1997. Mahogany seedlings grown in other parts of northern Australia are known to develop strong deep taps roots within the first year of growth, and this species is also tolerant of inundation and can survive on swampy soils (Robertson 2002). Therefore, given the shallow depth to groundwater, the KTC plantation probably quickly developed roots into the watertable.

Irrigation ceased around 2001 and the trees remained unirrigated until 2006. Watertable drawdown of up to 7 m occurred directly beneath the plantation and declines of 1–2 m occurred up to several-hundred metres beyond the trees. Irrigation re-commenced during 2006 but a distinct groundwater response has not been evident to date. Heuperman (1999) reported a similar watertable response beneath unirrigated trees planted in low permeability soil at Kyabram in the Shepparton Irrigation Region of northern Victoria. The watertable under the plantation at Kyabram was lowered by 2–4 m during an 11-year period from 1982 to 1993, which represented an average rate of watertable decline of 0.18–0.36 m yr$^{-1}$. The maximum rate of watertable decline beneath KTC plantation was 1.3 m yr$^{-1}$ between 2001 and 2006. Groundwater uptake by trees now appears to be maintaining the watertable depression beneath the plantation at approximately the same level it had reached by 2006. Provided irrigation does not exceed the trees’ water demands we might expect it to remain this way.

Scott Tree Farm and Mock Farm

Watertable maps and associated cross sections for Scott Tree Farm and Mock Farm are presented in Figure 20 to Figure 23. On the whole, there was no evidence of watertable decline or the formation of local watertable depressions beneath the trees since planting. Notably, the aquifer sediments at both sites are more permeable than at the KTC plantation (Figure 3) and therefore smaller watertable responses would be expected if trees were using groundwater. Significant groundwater rise occurred at both locations from the 1960s to the 1990s but the watertable appears to have been relatively stable during the past decade. The water level data suggest that the current watertable position is slightly lower than in 2001 when groundwater levels increased across the irrigation area in response to above-average rainfall (Smith et al. 2009).
Figure 18. Interpreted watertable elevation (2006–08) beneath KTC plantation
Figure 19. Watertable cross sections through KTC plantation
Section lines are indicated on Figure 18: (a) Section A–A', (b) section B–B', (c) section C–C’
Figure 20. Interpreted watertable elevation (2006–08) beneath Scott Tree Farm
Figure 21. Watertable cross sections through Scott Tree farm
Section lines are indicated on Figure 20: (a) section D–D’, (b) section E–E’
Figure 22. Interpreted watertable elevation (2006–08) beneath the Mock Farm sandalwood
Figure 23. Watertable cross sections through Mock Farm
Section lines are indicated on Figure 22: (a) section F–F’, (b) section G–G’
5.2.2. Groundwater modelling of KTC plantation

Watertable drawdown beneath the KTC plantation was simulated using the existing Ord Stage 1 groundwater flow model (Smith et al. 2006a). Because the direction of lateral groundwater flow is toward the plantation from all directions and the watertable is relatively deep (approximately 8 m below the soil surface) it is reasonable to assume that groundwater flow toward the plantation is balanced by water uptake by the trees. A uniform groundwater discharge rate of 0.7 mm d\(^{-1}\) was required to match the observed drawdown of approximately 7 m from 2001 to 2006. Excessive drawdown was simulated using a discharge rate of 1 mm d\(^{-1}\) and there was insufficient drawdown using a discharge rate of 0.5 mm d\(^{-1}\). After 2006, a reduced groundwater discharge rate of 0.4 mm d\(^{-1}\) was required to maintain the observed watertable depression beneath the trees without further drawdown or significant watertable recovery. At 0.7 mm d\(^{-1}\) the watertable continued to decline while at 0.3 mm d\(^{-1}\) it began to recover. The reduced rate of groundwater discharge from 2006 coincides with recommencement of irrigation; therefore, trees may have taken up more water from the soil derived from irrigation and become less dependent on groundwater.

The above modelling results suggested that the mean daily groundwater use by the Mahogany trees was around 0.7 mm d\(^{-1}\) (0.26 m yr\(^{-1}\)) when irrigation ceased in 2001. This resulted in the maximum observed groundwater draw-down rate in the centre of the plantation of 3.5 mm d\(^{-1}\) (1.3 m yr\(^{-1}\)). The rate of groundwater uptake by trees then apparently reduced to a value of around 0.4 mm d\(^{-1}\) (0.15 m yr\(^{-1}\)) by 2006. Integrated over the 275 ha site the above average discharge rates equate to total stand volumetric fluxes of approximately 1,960 KL d\(^{-1}\) (0.72 GL yr\(^{-1}\)) from 2001 to 2006 and 1,130 KL d\(^{-1}\) (0.41 GL yr\(^{-1}\)) from 2006 onward. Both estimates represent substantial groundwater discharge rates that are unlikely to be achieved using pumping wells. Based on expected well yields of 4-40 KL d\(^{-1}\) from the predominantly clay and silt sediment (O’Boy et al. 2001) a total discharge rate of 1,960 KL d\(^{-1}\) achieved by the trees would require 50–500 pumping wells, and a discharge rate of 1,130 KL d\(^{-1}\) would require 30–300 pumping wells.

Estimates of groundwater discharge derived from the groundwater modelling are necessarily sensitive to the adopted value of the sediment effective porosity, which was assumed to be 0.2 in the model. For example, if the true effective porosity was double the assumed value then the estimates of groundwater uptake by trees also would be double the values presented above. The total porosity of silt and clay is typically 0.5–0.6 (Bouwer 1978) but not all of the water in the pore space drains or can be extracted under field conditions. Therefore, the drainable porosity—also called effective porosity—is less than total porosity. The above estimates of groundwater uptake by trees based on drainable porosity 0.2 are considered to be conservative because it is likely that the decrease of the soil volumetric water content was greater. Data presented by Bridge and Muchow (1982) suggest that the volumetric water content of saturated Cununurra clay is around 0.5, which also indicates a total porosity of around 0.5. During drilling to install piezometers at KTC plantation, very dry soil conditions were observed above the capillary fringe of the watertable and within the zone where trees had dewatered the aquifer (Smith et al. 2006b). For example, measurements made on soil extracted during piezometer installation indicated that the volumetric water content of clay above the watertable was around 0.15 (Appendix H). Therefore, the pore space drained by the trees can be estimated as 0.5 – 0.15 = 0.35, which is significantly larger than the value 0.2 assumed for drainable porosity.

5.2.3. Ivanhoe pumping trial

The watertable response during a high capacity groundwater pumping trial on Ivanhoe Plain conducted nearby the KTC plantation (Smith et al. 2005) provides a useful comparison to watertable drawdown beneath the plantation. The two pumping well locations and a plot of stabilised watertable drawdown during the trial are presented in Appendix I. The mean discharge rates for the pumping wells over the entire trial were 4,492 KL d\(^{-1}\) from well 10/00 and 4,372 KL d\(^{-1}\) from well 11/00. Stabilization of watertable drawdown occurred after approximately two months of continuous pumping, indicating an analogous situation to KTC plantation in which the total groundwater withdrawal rate was approximately balanced by the rate of lateral groundwater flow into the drawdown area. Maximum drawdown near the
pumping wells after stabilization was around 1.5–2 m, which is only around one-fifth of the observed draw down beneath KTC plantation. Notably, the total pumping rate during the trial was a factor 4–5 times greater than the estimated groundwater uptake by the Mahogany trees during 2001 to 2006 and 7–8 times greater than the estimated groundwater use by trees since 2006. This difference between the sites reflects the difference in the permeability of the aquifer sediments and the abilities of the aquifers to conduct groundwater laterally.

The comparison illustrates the importance of local hydrogeological controls on the relative efficacies of tree planting and groundwater pumping wells for watertable management. The watertable benefit that can be achieved by planting trees or installing groundwater pumps depends critically on the local distribution of sediment types and their hydraulic properties. Groundwater pumping wells provide point discharges and to be effective the wells must be installed into sediment layers with large permeability and large capacity to transmit lateral flow (e.g., sand and gravel beds). Large groundwater extraction rates that may be beyond the capacity of trees are then possible. On the other hand, pumping wells are not a practical solution in areas with predominantly clay and silt sediments and poor transmissivity. In that situation a distributed network of tree roots with access to the watertable can extract groundwater more efficiently and affect the watertable over a larger area.

5.2.4. Analysis of daily watertable fluctuation

The piezometer water level records acquired in this study typically exhibited distinct diurnal (once per day) and semi-diurnal (twice per day) fluctuations, which correlated with diurnal and semi-diurnal fluctuations of atmospheric pressure. This pattern is shown in Figure 24 and Figure 25, which depict air pressure at ground surface recorded at Kununurra airport, and Figure 26 and Figure 27, which depict water level fluctuation in piezometer CO38 during the same time period. This piezometer is located directly outside of the trees at the southern corner of KTC plantation. Figure 25 and Figure 27 reveal the spectral characteristics of atmospheric pressure and water level in CO38, and show distinct peaks in spectral power at diurnal and semi-diurnal frequencies. The atmospheric tide is both gravitational and thermal in origin, with the semi-diurnal constituent having slightly greater power than the diurnal constituent. A similar relationship exists in the water level data from piezometer CO38 (i.e., the diurnal and semi-diurnal constituents have similar spectral power), which suggests that the observed water level fluctuation is mostly a response to barometric pressure fluctuation. Change of atmospheric pressure occurs instantly at the free water surface within the piezometer but it may be felt later, or not at all, within the aquifer formation, dependent on the resistance to pressure propagation through the unsaturated and saturated zones. Resultant pressure differences between the water column in the piezometer and the aquifer formation surrounding the piezometer inlet cause small flows of water in and out of the piezometer across the inlet. In such cases the piezometer behaves as a barometer with partial efficiency that depends on the hydraulics of the piezometer-aquifer system.

In some piezometers it was observed that the spectral power of the diurnal constituent was apparently enhanced relative to the barometric pressure signal, and that this may indicate an additional diurnal response of the watertable to evapotranspiration of groundwater. An example for piezometer CO40 is presented in Figure 28. In this case the spectral power of the diurnal constituent was approximately 10 times greater than the semi-diurnal constituent. Figure 29 depicts this relationship for each piezometer in the study, and for barometric pressure at Kununurra airport. Eight of seventeen piezometers showed evidence of enhanced diurnal water level fluctuation that may indicate evapotranspiration of groundwater by vegetation at those locations; 4 are located within KTC plantation (CO40, CO42, CO41 & CO39); 2 are located at Scott Tree Farm (CO51 & CO54); and 1 is located at Mock Farm (CO55). Additional detail for each piezometer and tabulated results are contained in Appendix J. Piezometers with enhanced diurnal fluctuation at KTC plantation are all located within the trees where significant drawdown of the watertable has occurred. Only piezometer CO38, which is located outside of the trees, does not indicate a daily cycle of groundwater evapotranspiration. This result is consistent with the previous analysis based on groundwater modelling. Spectral evidence of diurnal evapotranspiration of groundwater at Scott Tree
Farm and Mock Farm is less clear. This may be because evapotranspiration is lower or trees are not using groundwater at these sites.

Figure 24. Two-hourly air pressure records from Kununurra airport. This time series spans the same period as the water-level time series for piezometer CO38 presented following in Figure 26.

Figure 25. Spectral analysis of air pressure fluctuation at Kununurra airport.
Figure 26. Two-hourly water level records from piezometer CO38
Watertable depth below the ground surface was approximately 3 meters

Figure 27. Spectral analysis of water level fluctuation in piezometer CO38
The spectral signature is characteristic of barometric fluctuation with similar power at diurnal and semi-diurnal peaks.
Figure 28. Spectral analysis of water level fluctuation in piezometer CO40
The spectral signature contains an enhanced diurnal peak relative to barometric fluctuation, which suggests diurnal evapotranspiration of groundwater.

Figure 29. Evidence of evapotranspiration of groundwater based on enhanced diurnal fluctuation of the watertable
6. TREE WATER-USE INVESTIGATION

We measured the water use of trees at the KTC plantation, Scott Tree Farm and Mock Farm in order to determine if there was evidence of tree groundwater use. We did this by comparing trends in water use to seasonal patterns of rainfall, irrigation and soil water content, and by comparing the annual tree water use to the amount of water input to the site through rainfall and irrigation.

6.1. Methods

6.1.1. Transpiration

Tree water use was monitored with sap flow sensors installed during June 2006 at each site. Six randomly chosen (but apparently healthy) sandalwood and six host trees were monitored at both Scott Tree Farm and Mock Farm, and four mahogany trees were monitored at both KTCW and KTCE. Two probe sets were installed into each sample tree and the measurements recorded every 30 minutes by a data logger. The sap flow equipment (Figure 30) consisted of a heater probe and temperature probes upstream and downstream from the heater. In this configuration the temperature sensors measure the time it takes for the heat pulse to move upstream by diffusion and downstream by diffusion and sap flow to yield an estimate of sap velocity.

Two types of sap flow equipment were installed: one used the compensation technique (Greenspan Technology, Warwick, Queensland, Australia) and the other used the heat ratio technique (Burgess et al. 2001). The equipment was distributed so that both types were used at each site and in both sandalwood and host species within a site. With the compensation technique, the upstream temperature sensor is closer to the heater and so will warm sooner than the downstream sensor as heat diffuses through the sapwood. The downstream sensor then warms as heat travels through a combination of diffusion and advection of the heat pulse as sap flows up the tree; heat pulse velocity is calculated by measuring the time it takes for the upstream and downstream sensors to reach the same temperature after emission of a heat pulse. With the heat ratio method the upstream and downstream temperature sensors are placed equidistant from the heater and the heat pulse velocity is determined by measuring the ratio of upstream and downstream sensor temperatures for a given period after emission of the heat pulse. Department of Agriculture staff downloaded the sap flow data loggers monthly and changed and recharged batteries.

Small cores were taken from trees at the end of the dry season and wet season to measure the parameters used to convert heat pulse velocity to tree water use. At Scott Tree Farm and Mock Farm six host and six sandalwood trees were sampled, and six mahogany trees were sampled at both KTCW and KTCE. Analysis of sap flow data from the heat ratio instruments followed the methods of Burgess et al. (2001). The measured heat pulse velocity was corrected for probe misalignments during sensor installation, the effect of wounding from the installation of probe sets, and the thermal diffusivity of the wood being sampled. Heat pulse velocity was then converted to sap velocity by measuring the fractions of wood and water in the sapwood. A similar approach was taken to analyse the sap flow data from the compensation technique. The approach of Swanson and Whitfield (1981) was followed for wound corrections and the method of Edwards and Warwick (1984) was used to convert heat pulse velocity to sap velocity based on wood and water fractions in the sapwood. It was necessary to impose a “time-out” value for the compensation technique because the method cannot measure zero flow (Anonymous 1996). Values of sap velocity measured directly before dawn—when it was assumed that no sap flow was occurring—were used to set the time-out value. If it took longer than this after emission of a heat pulse for the upstream and downstream sensors to be at the same temperature, it was considered that no flow had occurred.

Sap velocity was converted to sap flow (i.e., the rate of water use by the sample tree) by measuring the amount of sapwood. This was determined from the wood cores taken at each site, either by observing colour differences between the sapwood and heartwood or using pH indicators to detect the sapwood-heartwood boundary. Measurements of sap velocity from
the four sensor pairs in each tree were then integrated across the measured sapwood area using the weighted average approach of Hatton et al. (1990).

Individual tree water use was up-scaled to stand water use by estimating the combined sapwood area within a stand of trees. A relationship between trunk diameter at breast height and sapwood area was derived for each tree species based on the trees from which the cores were taken. Total sapwood area per plot was derived by measuring the trunk diameter of all trees within 40 x 40 m (0.16 ha) plots at KTCW and KTCE, and within 40 x 25 m (0.1 ha) plots at Scott Tree Farm and Mock Farm. The diameter measurements were repeated every six months to allow for tree growth during the study and tree heights were measured at the same time. Daily volumes of water used within a plot were calculated at each site and converted to transpiration rates in millimetres per day by dividing by the plot area.

![Figure 30. Images of the sap flow sensors](image)

6.1.2. Estimation of rainfall, runoff, canopy interception and soil evaporation

Daily rainfall records were obtained from the SILO Patched Point Dataset for the climate stations closest to KTC plantation and Mock Farm. These were the Kimberley Research Station rain gauge (station 2014) located approximately 6.5 km from the mahogany blocks, and the Ivanhoe Station rain gauge (station 2013) located approximately 2.5 km from the sandalwood at Mock Farm. Rainfall data from the gauge at Scott Tree Farm was provided by ITC.

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Little information exists on runoff of rainfall in the Kununurra region. Muchow and Keating (1998) modelled 178 mm of runoff from annual rainfall of 772 mm beneath a first ratoon sugar cane crop on Kununurra clay, with the agricultural production simulator model (APSIM). We believe that runoff may be similar under the relatively open canopy of the Scott Tree Farm, but should be much less under the closed canopy at KTCW and Mock Farm. Consequently, we assumed annual runoff to be 150 mm at Scott Tree Farm, 100 mm at KTCE and 50 mm at KTCW and Mock Farm.

Interception of rainfall by the tree canopy depends on the leaf interception storage capacity, which is a product of the leaf surface area per unit ground area (leaf area index, LAI) and the average water holding capacity per unit leaf area (Calder 1986). Calder (1986) reviewed studies of different species and showed that species with a low storage capacity such as Eucalypts, had interceptions of around 10% of rainfall, while those with higher storage capacities, such as tropical hardwoods, had interception of 20 to 35%, with various annual rainfall amounts between 700 and 1600 mm. Other studies and reviews have reported almost identical ranges of canopy interception between 10% and 35% of rainfall, for different species, regions and rainfalls (Calder et al. 1986, Breda et al. 1995, Bruijnzeel 1997). Breda et al. (1995) reported that canopy interception was 23% of rainfall for an un-thinned stand of oak with an LAI of 5, and 15% of rainfall in a thinned stand with LAI of 2. We did not measure LAI in the current study, but based on basal area and visual estimation of the canopy we estimate that the LAI of the plantations of this study vary between >5 for the KTCW site down to <2 for ITC Scott Tree Farm. Based on the literature, we estimated canopy interception to be 25% of rainfall for KTCW, 20% for Mock tree farm, 15% for KTCE and 10% for Scott Tree Farm.

After subtracting canopy interception and runoff, the infiltrated rainfall was between 70% and 75% of the total annual rainfall. This number corresponded to soil moisture content measured during this study; the average increase in soil water content following discrete rainfall events was 80%. The apparent rainfall infiltration measured by soil moisture sensors varied; a large part of this variation could be due to not measuring rainfall at the individual plantations.

Estimates of soil evaporation from within the plantations were derived from running the tree growth model 3-PG (Landsberg and Waring 1997), which uses the Ritchie two-phase model of soil evaporation (Ritchie 1972). This model is not calibrated for the species examined in the current study; we used the parameter set of Eucalyptus camaldulensis as this species occurs naturally in the region. Although there are morphological and physiological differences between the species studied here and E. camaldulensis, we were able to simulate the development of a range of LAI under local climatic conditions and soils, resulting in what we believe to be representative soil evaporation rates. We controlled the growth rates of trees by altering the 3-PG soil fertility index to produce high and low LAI. The resulting annual evaporate rates we assumed were 100 mm for KTCW and Mock tree farm, 150 mm for KTCE and 200 mm for Scott Tree Farm.

We used these values and annual tree transpiration estimated from sap flow measurements to construct a crude water balance for each plantation. The water balance equation is:

\[ P + I = T + E + IL + R + L + \Delta S + D \]

where \( P \) = rainfall; \( I \) = irrigation; \( T \) = transpiration; \( E \) = soil evaporation; \( IL \) = canopy interception loss; \( R \) = runoff; \( L \) = net lateral flow of water away from the trees; \( \Delta S \) = the net change in soil water content and \( D \) = deep drainage.

We did not measure the lateral flow of water, and did not find information in the literature to estimate this. Therefore we did not take this into account in the water balance calculation. With the exception of the KTC plantation, we did not observe large gradients in groundwater depth that would induce significant lateral flow of water, but flow may be occurring none-the-less. There may have been flow of groundwater into the KTC plantation from the surrounding area, which would introduce error to our water balance calculation.
It was beyond the scope of this study to measure the amount of irrigation applied to plantations, and since tail water runoff is not monitored the amount of water added to the soil from irrigation events was therefore difficult to quantify; the volume of water applied to individual compartments within a plantation is not measured and we could not find any other information on irrigation efficiency in the area. We relied on soil moisture measurements to estimate the amount of water infiltrating the top 2 m of soil after irrigation events during the study period. The one irrigation event recorded at Mock Farm resulted in addition of 75 mm of water to the top 2 m of soil, while the average addition per irrigation event at KTC and Scott Tree Farm was 50 mm. We obtained irrigation records from the plantation managers and assumed these amounts per irrigation event.

Although soil moisture was measured at each plantation, we did not obtain a full annual cycle of measurements. Therefore, we could not quantify the net change in soil water content in our water balance calculation. Any excess of water inputs \((P + I)\) over outputs \((T + E + IL + R)\) would thus result in either a net increase in soil water content or drainage to the watertable. Conversely, if water outputs were greater than the inputs, this could reflect either a net uptake of soil water or uptake from the watertable.

We also compared changes in soil water content to tree transpiration over shorter time frames, when there were no inputs from rainfall or irrigation, to assess if uptake from groundwater was likely. Although this does not allow quantification of the annual amount of groundwater used by trees, it does provide evidence as to whether tree groundwater use is likely.

### 6.2. Results and Discussion

#### 6.2.1. Tree water use

The rates of tree water use varied between plantations, with highest rates at KTCW (Figure 31) and lowest rates at Scott Tree Farm (Figure 33). Annual total tree transpiration was 753 mm at KTCW, 468 mm at Mock Farm, 373 mm at KTCE and 345 mm at Scott Tree Farm (Table 7). The differences in tree water use between plantations reflected differences in tree size, with highest stem area measured at breast height at KTCW, next highest at Mock Farm, then KTCE and lowest at Scott Tree Farm (Figure 34). Although we did not measure leaf area, it was obvious that relative differences in LAI between plantations followed the trend in stem area. The rate of evapotranspiration at a site is generally proportion to LAI (Grier and Running 1977); therefore, it is not surprising that rates of tree water use measured in this study reflected tree and canopy size.

The seasonal pattern of tree water use was examined for evidence of plant water stress, and compared to trends in soil water content to determine if there was any evidence of tree groundwater use. If trees are in water stress then a reduction of transpiration rate is expected. We compared transpiration rates to a reference evapotranspiration, FAO56, published by the Food and Agriculture Organization (FAO) of the United Nations. The FAO56 represents the maximum evapotranspiration that would occur from a well watered and well managed crop under particular climate conditions, calculated from the Penman-Monteith equation (Allen et al. 1998).

The transpiration rate of trees at KTCW generally followed the pattern of FAO56; this relationship did not alter even during times of potential water stress during the dry season and prior to irrigation events (Figure 31). There was variation of water availability in the top 2 m of the soil profile at KTCW (Figure 13 and Figure 14); for example, by the end of the study gravimetric soil water content was approximately 14% in the top 100 cm, 20% at 150 cm and 14% at 200 cm. These values are close to or below the average wilting point of Cununurra clay, which is 16% gravimetric water content (Bridge and Muchow 1982). Despite this low plant available soil water, tree transpiration rate did not alter in relation to FAO56 reference evapotranspiration, suggesting that water below 2 m was accessed, either stored in the soil profile below 2 m, or from groundwater. Soil water content decreased with depth below 150 cm (Figure 13), and during drilling was found to be dry until the capillary fringe of the watertable was reached at 5 m (Appendix H). Therefore, it seems likely that trees at
KTCW were accessing water from groundwater or the capillary fringe of the watertable, resulting in continual high rates of transpiration throughout the year.

The sap flow data from KTCE suggest that transpiration rate at this site was more influenced by changes in soil water content, than it was at KTCW. Soil moisture data is not available at KTCW for comparison with KTCW during the drying period after the end of the wet season in 2008. However, the tree transpiration rate at KTCE did decrease during this period in relation to FAO56 (Figure 31). Another example of transpiration deviating from the pattern of FAO56 was during November when the transpiration rate decreased markedly while the FAO56 was increasing (Figure 31). At the same time, the gravimetric soil water content also decreased to 22% or lower depending on soil depth (Figure 13). Although this is above the wilting point, it may have resulted in relatively low plant available water. Bridge and Muchow (1982) reported that the wilting point of Cununurra clay increased with depth; at the deepest level measured, 90 cm below the surface, it was 18% gravimetric water content. In addition, bulk soil water content may be higher than that occurring in the immediate vicinity of plant roots (Schmidhalter 1997), so that plant available water may be lower than what is indicated by bulk soil water content. Okali and Dodoo (1973) found that *Khaya senegalensis* had a high degree of stomatal sensitivity to soil water content, with stomata closing with only relatively low water stress so that transpiration rate decreased significantly. This may be an adaptation to drought conditions, as closing stomata and reducing transpiration conserves moisture in the plant and the soil. Therefore, the decrease in soil water content may have caused trees at KTCE to have reduced rates of transpiration. After the wet season commenced and the soil water content in the top 200 cm of soil increased, tree transpiration also increased. This implies that trees at KTCE do not have access to the same deeper water sources as trees at KTCW. In comparison, over the same time period the soil water contents at KTCW were lower than at KTCE (18% at 50 cm, 22% at 100 cm, 20% at 150 cm and 14% at 200 cm), but tree transpiration rates were higher and continued to follow the trend of FAO56 reference evapotranspiration.

Figure 31. Daily transpiration and irrigation events at the KTCW and KTCE Comparison with FAO56 reference daily evapotranspiration and daily rainfall recorded at the Bureau of Meteorology Kimberley Research Station
Figure 32. Daily transpiration and irrigation events at Mock Farm
Comparison with FAO56 reference daily evapotranspiration and daily rainfall recorded at Ivanhoe Station

Figure 33. Daily transpiration, irrigation events and daily rainfall at Scott Tree Farm
Comparison with FAO56 reference daily evapotranspiration recorded at Kimberley Research Station
Apparent differences in tree access to deep soil water or groundwater may have contributed to differences in the tree growth rates between KTCE and KTCW. At the time of this study, the African mahogany trees at KTCE were around half the size of trees at KTCW (Figure 34) and the transpiration rate was also approximately half. Although both sites were planted at the same time and with the same tree density, the stem area at breast height of trees at KTCE in May 2008 was approximately 9 m² ha⁻¹ compared with 20 m² ha⁻¹ at KTCW. The marked difference between tree growth rates at the two sites appears to be the result of a natural biophysical gradient in the soil and groundwater conditions across the southeast part of the plantation rather than differences in management of the compartments, as aerial photography shows a distinct boundary in greenness (related to leaf area) that does not correspond to the edges of compartments (Figure 10a). It is possible that soil or groundwater salinity is higher at KTCE than at KTCW, or there may be a hardpan preventing access to groundwater by trees. This is unknown as we did not sample the soil at KTCE or drill to the groundwater. The affect of site differences on growth rates may have become less prominent now that irrigation of the plantation has re-commenced. Further measurements are required to determine why tree growth at the KTCE site was lower than at the KTCW site. The variation in growth at the KTC plantation demonstrates the importance of a thorough site assessment prior to planting tree crops.

Only a limited amount of soil moisture data was recorded at Mock Farm (Figure 16) where a temporary water deficit was apparent during the latter half of 2007. It appeared that the soil water content was significantly less at this site than at the KTC plantation and Scott Tree Farm. At the end of August in 2007 the gravimetric soil water content was as low as 12% to 18% in the upper 2 m of the soil profile, which is at or below the plant wilting point. Despite this, the relationship between evapotranspiration and FAO56 did not vary with rainfall and irrigation (Figure 32) and the transpiration rate did not appear to be limited by soil water availability. The trees may have been periodically accessing deeper soil water or possibly groundwater from the capillary fringe. The soil water content appeared to decrease with depth to at least 2 m but it may have increased at greater depth or a significant capillary fringe may be present. The relatively infrequent irrigation at Mock Farm may encourage tree roots to develop at greater depth where the soil water content is likely to be less variable.

Soil water stress did not seem to limit transpiration at Scott Tree Farm; the transpiration rates of sandalwood trees did not vary significantly throughout the year, and although there were periods of low host tree transpiration, this was not related to periods of low soil water content (Figure 13 and Figure 33). Soil water content was generally higher at Scott Tree Farm than at Mock Farm and KTC plantation, reflecting the more frequent irrigation of the plantation. Gravimetric soil water content at 100 cm and 150 cm remained above 22% and varied little.
throughout the measurement period (Figure 17). Interestingly, soil water content at 30 cm and 50 cm depth was lower during the wet season than during the dry season. As sandalwood and host transpiration rates were not higher in the wet season, this indicates that effective irrigation applied over the dry season was greater than the effective rainfall received in the wet season.

The diurnal trend in transpiration rate may also provide information on the degree of water stress that plants are experiencing. Water stress results when water is not supplied from the soil to the leaf surface at a rate sufficient to meet evaporative demand from air saturation deficit or biophysical demand. This can result from high evaporative demand, relatively low soil water content, or low hydraulic conductivity within the plant, and results in decreased transpiration rates. Decreased transpiration rates as a result of insufficient water to meet demand would be most likely to occur in the afternoon when air temperature and vapour pressure deficits are highest. Kununurra experiences extremely hot temperatures and low humidity, and evaporation remains high throughout the year with monthly averages between 6 mm d\(^{-1}\) and 10 mm d\(^{-1}\). During this study, the transpiration rate of trees at all sites was usually highest in the morning and then decreased from around 9 am as the vapour pressure deficit increased (Figure 35). Trees may have been responding to increased air temperature and vapour pressure deficit by opening stomata and photosynthesising in the morning when it was relatively cool and humid, and closing stomata in the afternoon to conserve water when the evaporative demand was large. At KTC and Mock Farm this pattern was more pronounced in the dry season; diurnal patterns in vapour pressure deficit were similar in the wet and dry seasons, so the stronger stomatal response to vapour pressure deficit was apparently related to lower soil water contents. Trees at Scott Tree Farm, particularly the host species, appeared to have a weaker response to vapour pressure deficit than trees at the other sites, and there was little difference in the response between the wet and dry seasons. The higher soil water content at Scott Tree Farm may have resulted in a weaker stomatal response to vapour pressure deficit throughout the day, and indicates that soil water content is not limiting transpiration rates. The sandalwood trees seemed to have a stronger response to increasing vapour pressure deficit than the host trees at Scott Tree Farm in the dry season. Radomiljac et al. (1999) measured photosynthesis and stomatal conductance of Indian sandalwood seedlings, which peaked early in the day when vapour pressure deficit was low and decreased throughout the day as the vapour pressure deficit increased. Nevertheless, they concluded that the photosynthesis and water use of sandalwood was largely dependent on how its host plant responded to environmental conditions.

There were some differences in the diurnal trends of transpiration between KTCW and KTCE that could indicate differences in access to deep soil water or groundwater. During the wet season when soil water contents were high, transpiration rates were very similar at both sites throughout the day. In the dry season, the transpiration rate decreased earlier in the day at KTCE than at KTCW, indicating that more water stress was experienced at KTCE. Curiously, at KTCE, sap velocity initially decreased in the morning but the trees apparently recovered and continued transpiring at a higher rate during the afternoon. This phenomenon was recorded in all sap flow sensors employed at this site, so appeared to be a real effect unless an artefact of some logger interference not experienced at the other sites. Despite the evidence that trees at KTCW had access to groundwater, transpiration decreased early in the day as vapour pressure deficit increased, indicating a relatively high sensitivity of stomata to vapour pressure deficit in this species. Okali and Dodoo (1973) found that Khaya senegalensis had small transpiration rates even in well-watered conditions; transpiration of seedlings was only 17% of evaporation from blotting paper discs. This could indicate the species has tight stomatal control of water loss that may limit the transpiration rate and consequently photosynthesis and growth under water limited conditions.

6.2.2. Annual Water Balances

The water balance analysis suggested that, of the plantations studied, only the mahogany trees at KTC were likely to be using groundwater. At KTCW the estimated evapotranspiration during 2006–07 was 151 mm greater than the estimated infiltration of rainfall and irrigation (Table 7). This difference, equivalent to 15% of evapotranspiration, could be due to either
uptake of soil water or groundwater. Unfortunately, due to instrumentation difficulties, we did not record soil moisture over a full annual cycle and could not calculate the net change in soil water content for the water balance analysis. Over the period of soil water monitoring from August 2007 to April 2008, there was approximately 55 mm net uptake from the top 50 cm of soil (calculated from data shown in Figure 15); however, much of this monitoring occurred outside the period of the water balance calculation. Within the time that both soil water content and tree sap flow was measured, we compared tree transpiration to the net change in soil water content, over certain periods when little or no rainfall or irrigation was received, and found that groundwater uptake was likely. For example, during October 2007, tree transpiration was 81 mm, while the decrease in soil water content over 2 m was 46 mm. Similarly, from March 2008 to April 2008 soil water content decreased by 75 mm while tree transpiration was 150 mm (20 mm of rainfall was also received over this period). As stated earlier, this discrepancy could be due to uptake by trees of water from deeper in the soil profile, but as soil was dry below 2 m until the capillary fringe of the watertable, it seems likely that the extra water was sourced from groundwater.

Figure 35. Average diurnal sap velocity during the 2006–07 wet and dry seasons (a, b) African mahogany at KTCW and KTCE, (c, d) sandalwood and host species at Scott Tree Farm, (e, f) sandalwood and host species at Mock Farm
Table 7. Water balances at KTCW, KTCE, Scott Tree Farm and Mock Farm
August 2006 to July 2007; a water balance was calculated for KTC by integrating KTCW and KTCE based on the proportions of the plantation occupied by trees of high and low growth rates; crop factors are approximate and indicate only relative differences between sites and other published data

<table>
<thead>
<tr>
<th>Water balance element, mm</th>
<th>KTCW</th>
<th>KTCE</th>
<th>KTC integrated</th>
<th>Scott</th>
<th>Mock</th>
</tr>
</thead>
<tbody>
<tr>
<td>2. Rainfall</td>
<td>736</td>
<td>736</td>
<td>736</td>
<td>636</td>
<td>760</td>
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<tr>
<td>3. Rainfall interception</td>
<td>184</td>
<td>110</td>
<td>162</td>
<td>64</td>
<td>152</td>
</tr>
<tr>
<td>4. Rainfall runoff</td>
<td>50</td>
<td>100</td>
<td>65</td>
<td>150</td>
<td>50</td>
</tr>
<tr>
<td>5. Effective rainfall</td>
<td>502</td>
<td>526</td>
<td>509</td>
<td>422</td>
<td>596</td>
</tr>
<tr>
<td>6. Effective irrigation</td>
<td>200</td>
<td>50</td>
<td>155</td>
<td>350</td>
<td>75</td>
</tr>
<tr>
<td>7. Rainfall - runoff + irrigation (2-4+6)</td>
<td>886</td>
<td>686</td>
<td>826</td>
<td>836</td>
<td>785</td>
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<tr>
<td>8. Tree transpiration</td>
<td>753</td>
<td>373</td>
<td>639</td>
<td>345</td>
<td>468</td>
</tr>
<tr>
<td>9. Soil evaporation</td>
<td>100</td>
<td>150</td>
<td>115</td>
<td>200</td>
<td>100</td>
</tr>
<tr>
<td>10. Evapotranspiration (3+8+9)</td>
<td>1037</td>
<td>633</td>
<td>916</td>
<td>609</td>
<td>720</td>
</tr>
<tr>
<td>Water balance (7-10)</td>
<td>-151</td>
<td>53</td>
<td>-90</td>
<td>227</td>
<td>65</td>
</tr>
</tbody>
</table>

The groundwater modelling indicated that since 2006 there has been a net groundwater uptake of 150 mm yr⁻¹, based on changes in the watertable depth beneath KTCW, measured in piezometers close to where sap flow measurements were made (Section 5.2.2). The similarity of this result to the estimated excess in evapotranspiration over rainfall and irrigation is probably coincidental given the rudimentary nature of our water balance calculation. However, together these measurements provide independent evidence that trees at KTCW are using groundwater or water from the capillary fringe, in the order of 100 to 200 mm yr⁻¹.

At KTCE the estimated evapotranspiration was 40% lower than at KTCW due to lower tree transpiration and estimated canopy interception from the smaller trees. Although the input of water through irrigation was 150 mm less at KTCE than at KTCW (due to less frequent irrigation of the compartment in which water balance calculations were made), evapotranspiration was still 53 mm yr⁻¹ less than rainfall and irrigation (minus runoff). This indicates that the soil water content increased by this amount, or that there was net recharge to the watertable. The water balance of KTCE and KTCW was integrated to give an indication of net groundwater recharge for the entire KTC plantation. The proportion of the plantation occupied by the trees of different size and apparent canopy area was estimated from the clear boundary evident in aerial photography (Figure 10a). Approximately 30% of the plantation was occupied by smaller trees, represented by the KTCE water balance, and the remaining 70% occupied by larger trees represented by the KTCW water balance. The integrated evapotranspiration of the two sites was estimated to be 90 mm greater than the average infiltration from rainfall and irrigation during 2006–07. Thus, overall there appeared to be a net uptake of either soil water or groundwater by the plantation.
At Mock Farm evapotranspiration was 720 mm yr\(^{-1}\), 65 mm yr\(^{-1}\) less than the estimated rainfall and irrigation minus runoff. Evapotranspiration at Scott Tree Farm was lowest of all the plantations, at 609 mm yr\(^{-1}\), which was 227 mm yr\(^{-1}\) less than rainfall and irrigation minus runoff. This amount is likely to be greater than the potential errors in the water balance calculation, and would result in increased soil water content or net recharge to the watertable. We cannot calculate errors for the components of the water balance that were modelled or estimated based on the literature. Benyon \textit{et al.} (2006) stated that the majority of error in water balance calculations was derived from sap flow measurements. The standard error of average transpiration over the period of sap flow measurements was 9\% for KTCW, 11\% for KTCE, 5\% for Mock host trees and 13\% for Mock sandalwood trees and 8\% for Scott Tree Farm host trees and 12\% for sandalwood trees. Therefore, the results for KTCE and Mock Farm (indicating net groundwater recharge or soil water increase of 8\% and 9\%, respectively, above evapotranspiration), is within the bounds of error in the calculation of evapotranspiration. In contrast, the results for other sites are more convincing, with net groundwater recharge or increased soil water content 37\% above evapotranspiration at Scott Tree Farm and groundwater uptake or soil water depletion equivalent to 15\% of evapotranspiration at KTCW.

Unlike KTCW, the water balance results for Scott Tree Farm were not reflected in any changes in depth to groundwater, which has been stable over the last decade (Section 5.2.1). There was no evidence from soil water measurements that water was recharging below 2 m and there was no net increase in the soil water content over the duration of the study. We may have underestimated other components of the water balance; for example, soil evaporation or runoff may have been higher than we allowed for. In addition, we did not include any estimate of lateral movement of water in the water balance calculation. In section 5.2.1 we noted that the aquifer sediments at Scott Tree Farm are more permeable than at the KTC plantation; therefore smaller watertable responses would be expected from either net uptake from or recharge to the watertable.

Differences in the transpiration rate between plantations and potential use of groundwater by trees may be related to the depth to watertable at the time of planting, and the irrigation frequency. At the time of planting, the groundwater was shallower at KTC plantation than at the other plantations; the watertable was initially 0–2 m below the ground surface (depending on the time of year and location in the plantation) in comparison to more than 6 m at Scott Tree Farm and Mock Farm. Therefore, the watertable would have been more easily accessible to trees at KTC. However, groundwater at 6 m would be within the potential rooting zone of many tree species; for example, Cannadell \textit{et al.} (1996) found that the average rooting depth for plants that that experience a long dry season was 5.2 m. Dell \textit{et al.} (1983) observed \textit{Eucalyptus marginata} roots at depths of up to 40 m in the south west of Western Australia. In addition, because there is capillary rise of groundwater within the soil matrix the soil is saturated to a level that is above the watertable elevation measured using a piezometer or monitoring well. Typical values of the thickness of the capillary fringe above the watertable vary from 0.1–0.3 m in sand to greater than 2–4 m in clay (Bear 1972). Capillary rise in Cununurra clay appears not to have been measured but could be significant particularly where the clay is uniform. However, even for deep rooted species, the majority of roots are close to the soil surface (Jackson \textit{et al.} 1996) and if soil water content in the surface remains high trees may be less likely to invest resources in developing deeper roots. Frequent irrigation, particularly at Scott Tree Farm, may have slowed root growth towards the watertable. By contrast, the lack of irrigation at KTC between 2000 and 2006 would have encouraged growth of deeper roots to follow the falling watertable. Root density at the watertable or capillary fringe is probably greater at KTC in comparison to the other plantations, even though the depth to groundwater is now similar at all three plantations. Continual use of groundwater by trees at KTC plantation allowed larger growth rates and larger transpiration in comparison to the other plantations.

Although there was no clear evidence of net annual groundwater uptake by trees at Mock Farm, the infrequent irrigation and relatively low soil water content may be encouraging growth of roots toward the watertable. Roots may already be present near the zone of saturation and using groundwater when the soil water content is limiting. It appeared that tree
trees were active to at least 2 m depth, because the soil moisture decreased with depth to 12% at 2 m below the ground surface, which is less than the wilting point of Kununurra clay (Bridge and Muchow 1982). Although on an annual basis water input from rainfall and irrigation was similar to or greater than evapotranspiration, at different times of the year there appeared to be imbalances between water requirements and water availability that result in transient water deficits. For example, the cumulative evapotranspiration was greater than effective rainfall and irrigation during late-2006 (Figure 36). This indicates that trees at Mock Farm were either using stored soil water or periodically accessing deeper soil water or groundwater during times when soil water content was limiting.

A similar pattern was observed at KTCE; although over an annual cycle there was an approximate balance between evapotranspiration and rainfall plus irrigation, at certain times of the year cumulative evapotranspiration was greater than water inputs, indicating either soil water depletion or groundwater uptake. This did not happen at Scott Tree Farm; cumulative rainfall plus irrigation was approximately balanced by evapotranspiration during the first few months of the study but rainfall and irrigation appeared to be in excess from late-2006 (Figure 36). The wetter conditions at Scott Tree Farm may have been detrimental to growth; frequent flood irrigation may result in waterlogging of the soil surface which can cause anoxia in the root zone, and can also increase the likelihood of fungal infections (Jurskis 2005). The trees at Scott Tree Farm were smaller than at the other sites; the average tree diameter was half that at Mock Farm where the trees are only one year older. We also observed that several trees died during the duration of the study at Scott Tree Farm.

6.2.3. Evapotranspiration of plantations relative to other natural and agricultural systems

The rates of evapotranspiration measured during this study (from 600 to 1,100 mm yr⁻¹, Table 7) were within the range reported for some woodland ecosystems in northern Australia. Evapotranspiration from unirrigated, native woodland or savanna ecosystems in northern Australia has been estimated between 400 mm yr⁻¹ (Leuning et al. 2005) to 1,100 mm yr⁻¹ (Cook et al. 1998). For example, the tree water use of riparian vegetation near Daly River in the Northern Territory (with twenty percent greater rainfall than Kununurra and similar evaporation) was between 650 mm yr⁻¹ and 1,500 mm yr⁻¹ (O’Grady et al. 2006b). Tropical woodland near Howard River close to Darwin had annual evapotranspiration of 1,100 mm yr⁻¹ (Cook et al. 1998), and evapotranspiration of savanna vegetation was 650 mm yr⁻¹ near Katherine (Hutley et al. 2001) and 460 mm yr⁻¹ (averaged over 2 years) in north Queensland (Leuning et al. 2005). However, these natural systems were unirrigated; the trees at KTC plantation, Scott Tree Farm and Mock Farm were irrigated during dry seasons and therefore greater evapotranspiration rates might be expected. In addition, the native woodlands and savannas have lower tree density and leaf area index than the plantations measured in the ORIA in this study.

As far as we are aware there is little information published on the evapotranspiration rates of irrigated crops in the ORIA. From the literature available it appears that the estimated evapotranspiration rates of trees in this study were relatively low compared with other crops. For example, Muchow and Keating (1998) modelled the evapotranspiration of sugarcane in the ORIA as between 2,500 and 3,000 mm yr⁻¹, although this was not actually measured. The growing season evapotranspiration of irrigated cotton, safflower and kenaf was estimated from changes in soil water content measurement at the Kimberley Research Station (Stern 1965, 1966, Muchow and Wood 1981), and appeared to be greater than the rates measured in the current study. For example, average evapotranspiration of an irrigated safflower crop was 3.1 mm day⁻¹ over the growing season, compared with an average rate of 2.8 mm day⁻¹ at KTCW, the site where we measured the highest evapotranspiration. Maximum growing season evapotranspiration divided by either pan evaporation or reference evapotranspiration calculated with the Penman-Monteith equation was greater than 1 for irrigated safflower (Stern 1965), cotton (Stern 1966) and kenaf (Hibiscus cannabinus, Muchow and Wood 1981), but was much lower than this towards the end of the growing season. The authors of these studies concluded that advection of energy and high crop surface roughness caused the high rates of evapotranspiration. By comparison, in the
current study, we estimated that the ratio of evapotranspiration of the tree crops to FAO56 reference evapotranspiration varied between 0.3 at Scott Tree Farm to 0.52 at KTCW. However, water use of the annual crops cited above was only measured during the growing season; annual evapotranspiration rates were not given so we cannot directly compare the water use here.

Figure 36. Cumulative evapotranspiration, rainfall and irrigation infiltration 1st August 2006 to 31st July 2007: (a) KTCW, (b) KTCE, (c) Scott Tree Farm, (d) Mock Farm
It is possible that we have underestimated evapotranspiration from the plantations due to error in the estimation of water balance components. As stated above, the standard error of the sap flow measurements varied between 5% and 15%. There were other potential sources of error that we did not quantify, such as scaling plot based measurements of tree water use to give plantation water use. An underestimate or overestimate of the tree diameter and sapwood area (Appendix L) would result in a proportional error in the calculated transpiration. To limit damage from cutting down trees the wound size caused by sensor installation was not measured for all trees with sensors. The wound created during installation of probe sets causes the measured heat pulse velocity to be slower than the actual sap velocity and a correction must be applied. If the true wound size was greater than the average of measurements made in this study then sap flow would be underestimated and vice versa. In addition, we did not directly measure soil evaporation or canopy interception.

If the estimated evapotranspiration rates for the tree systems in this study are indicative for the ORIA then tree plantings might require less irrigation than the crops they replace during the peak growing season. This would tend to reduce the potential for irrigation-induced groundwater rise during dry seasons if trees are irrigated according to their water requirements. Tree crops also actively transpire throughout the year and may allow less deep drainage of infiltrated rainfall during wet seasons than annual crops that are in fallow during the wet. In addition to being inactive during the wet season, annual crops exhibit large differences in transpiration throughout the growing season (Stern 1965, 1966, Muchow and Wood 1981). In comparison, we found that although there was significant variation in transpiration of tree crops there were no marked seasonal differences. The irrigation requirements of tree crops may therefore be more predictable and easier to manage with less chance of applying excess water.
7. SYNOPSIS OF THE STUDY RESULTS

Tree plantings in the ORIA might be beneficial to maintaining watertables at depth if they reduce groundwater recharge relative to other crops or if they increase groundwater discharge. In the first instance, recharge may be reduced under trees, relative to that under shallow-rooted annual crops, due to their perennial growth and deep root systems resulting in extraction of water from greater depths in the soil profile and water use throughout the year. In the second instance, trees grown over a shallow watertable may be able to directly use the groundwater, thereby increasing the rate of groundwater discharge and reducing the amount of irrigation they require.

Annual crops in the ORIA are generally grown with irrigation during dry seasons, as during the wet season higher temperatures and risk of soil waterlogging creates less favourable growing conditions. Farmland that is used to grow annual crops is mostly in fallow during wet seasons when cultivating wet Cununurra clay soil is difficult. Smith (2008) concluded that groundwater recharge and watertable accretion during wet seasons is significant in the ORIA and appears to exert a larger control on watertable level than irrigation. Trees, which grow throughout the year, utilize water throughout the wet season. In addition, trees have the potential to use more rainfall that is stored in the soil profile than annual crops because of their deep-rootedness and ability to exploit a greater depth of soil.

The results of this study indicate that trees at the KTC plantation use groundwater directly, and have done so for the past decade. This conclusion was supported by analysis of the historical groundwater depth data, measurements of tree water use and calculation of the site water balance. Trees at the KTC plantation probably developed tap roots into the shallow watertable as seedlings and then developed deeper root systems to follow the falling watertable. Current groundwater use by the trees appears to be maintaining the watertable depression beneath the plantation at roughly the same depth. Modelling indicates that recent groundwater use by trees is less than it was in the past; this could be due to the greater depth of the watertable or more frequent irrigation resulting in less dependence of trees on groundwater. It is possible that a balance between watertable depth, groundwater uptake, and tree growth has been reached.

Scott Tree Farm and Mock Farm are more typical of sandalwood plantations on Ivanhoe Plain. The trees were planted over relatively deep (6–8 m depth) watertables, and were less likely to access groundwater as young trees. The historical groundwater depth data, measurements of tree water use and calculation of water balance for Scott Tree Farm suggested that trees were not using groundwater at that site. The results for Mock Farm were mixed. The annual water balance for Mock Farm suggested that water use by trees was approximately met by rainfall and irrigation without need for groundwater uptake; however, the daily water balance indicated periods of water deficit in shallow soils and that trees apparently accessed soil water from below 2 m depth, or groundwater in the capillary fringe. It is possible that the trees have developed deeper roots to the top of the saturated zone although there is no evidence of watertable decline beneath the trees since planting.

The evapotranspiration rates of plantations were low in comparison to the peak rates reported for other irrigated crops in the ORIA. The low rates reported here could be the result of error in our water balance calculation, but could also indicate that during the peak growing season trees have lower irrigation requirements than annual crops. There was evidence from Scott Tree Farm that irrigating trees too frequently may discourage growth of deeper root systems to exploit soil water or groundwater at greater depth. Over-moist or waterlogged soil might also be detrimental to tree health by encouraging fungal diseases, and ultimately leading to reduced transpiration and growth rates.

Although peak transpiration rates of tree crops may be lower than annual crops, tree crops maintain more consistent rates throughout the year than annual crops, and remain active during the wet season. Relatively stable water use makes it easier to predict irrigation requirements and can reduce the likelihood of excess irrigation water being applied.
The results of the study show that tree crops have the potential to obtain part of their water requirement from groundwater. The water balance outcome was greatly dependent on the amount and frequency of irrigation applied. Even if trees do use groundwater at certain times when the soil water is limited this would only contribute to reduced groundwater recharge if irrigation at other times is carefully controlled. If annual rainfall minus runoff plus effective irrigation is greater than evapotranspiration then a net input of groundwater to the aquifer will occur, even if trees episodically use groundwater during the year. Nevertheless, if the groundwater input is less than deep drainage from alternate crops then trees may provide an overall benefit.

Watertable response to tree planting will vary across the irrigation area dependent on the watertable depth, local soil and aquifer properties and management practices. Significant watertable drawdown may occur beneath trees if the underlying aquifer has small transmissivity (e.g., Martin’s Location and Green Location). Targeted tree planting may afford a measure of control over the local watertable level but transpirative groundwater discharge beneath plantations may ultimately lead to accumulation of salt that could become detrimental to tree growth in the long-term, or pose a future salinity risk should the watertable rise again.

Growing trees above a shallow (2–4 m depth) watertable in areas where the underlying aquifer is more transmissive presents an alternative scenario. This could allow the trees to obtain part of their water requirement from groundwater and minimise the likelihood of a local watertable depression and salt accumulation beneath the plantation. It is possible that this circumstance already occurs on Packsaddle Plain where the depth to watertable is maintained by the hydraulic head in Lake Kununurra and most areas are underlain by very transmissive sand and gravel beds.

If trees are to be planted for the purpose of lowering the watertable in areas with low-permeability aquifer sediment then the concept of ‘roaming’ plantations discussed by Silberstein et al. (1999) may warrant further investigation. Under this concept, tree plantations would be grown for single rotations to lower the watertable at particular sites. Following harvesting of the trees, the plantations would be shifted to new locations and other crops planted in their place. In addition to careful consideration of the salt balance, the practicality of changing between trees and annual crops and the potential economic returns from this type of management would need to be assessed.

Our conclusions on the potential for tree crops to use groundwater or maintain watertables at depth in the ORIA are constrained by limitations in our methodology. Ideally all components of the water balance should be measured directly to increase the certainty around estimates of groundwater use. Alternatively, measurements of the stable isotopes of water in trees could be compared to the isotopic signatures of different source waters (rainfall, soil water and groundwater) to determine if trees are using groundwater (Rundel et al. 1989), although the addition of irrigation water may complicate this type of analysis.

More research is also needed on how site conditions (such as depth to groundwater, soil texture and salinity) and management (for example, planting configuration and irrigation frequency) impacts the water use and growth of trees. The results of this study indicate that irrigation frequency and amounts may exceed water requirements. However, although on an annual time scale evapotranspiration may be equivalent to rainfall, seasonal imbalances may still occur between water supply and demand and if trees have not developed deep roots may not be able to access deep soil water or groundwater. Therefore, further work is needed on how irrigation frequency affects plant water stress, the development of deep roots and groundwater use. Additional physiological measurements would help determine plant water stress and give insight into the water requirements of tree crops in the ORIA and how irrigation frequency and access to groundwater affect growth.

In addition, the sustainability of groundwater use by trees should be investigated, in terms of how tree groundwater use might vary as plantations age, impacts on groundwater depth, the extent of salt accumulation in the root zone, and how this impacts tree growth. This could be achieved by longer term studies, or with field trials comparing tree plantings with shorter
rotation crops. We recommend monitoring of the groundwater under the KTC Mahogany stand be continued to determine whether the trees have reached a steady state with their watertable. Maintaining longer term assessment of the sandalwood stands would seem warranted to determine if they explore to the watertable and perhaps lower it.

A critical factor influencing our ability to assess the older mahogany trees was a lack of understanding of the hydraulic properties of the Cununurra clay, particularly the capacity of the clay to store and yield water under different conditions (e.g., gravity drainage, preferential recharge flow, and suction induced by plant roots). We recommend detailed follow-up work to address this knowledge gap. To derive better estimates of water movement through and within the unsaturated and capillary zones, an improved understanding of the mechanisms for preferential flow and bypass flow associated with structural features in the clay (caused by swelling and shrinking) is required. This work would be particularly valuable if intensive field investigations can be undertaken.
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8. APPENDICES
APPENDIX A
Timeline of agricultural development in the Ord River irrigation area, 1913–2008
APPENDIX B

Chronological images of KTC plantation, 1972–2008
APPENDIX C
Chronological images of Scott Tree Farm, 1972–2008
APPENDIX D
Chronological images of Mock Farm, 1972–2008
APPENDIX E

Layout map of Scott Tree Farm
APPENDIX F

Example calibration curve for MP406 soil moisture probe in Cununurra clay

Description:
A second-order-polynomial calibration curve was established for each of the twenty MP406 soil moisture probes used in this study.

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APPENDIX G

Soil moisture data from two sites on Ivanhoe Plain

Description:
This data, provided by Dr Riasat Ali from CSIRO Land and Water, was collected for a study of irrigation scheduling for water and salinity management in the ORIA (report in preparation). It is presented here for the purpose of comparing the soil moisture measurements collected in this study using the MP406 soil moisture probes with soil moisture measurements determined by collecting soil samples in the field and analysing the soil moisture content of the samples using standard laboratory methods of oven drying and weighing.

In the study conducted by Dr Ali, the two field sites denoted KRS7A-1 and KSR7A-2 were located in block 7A at the Kimberly Research Station (KRS), which in 2004 had an irrigated maize crop grown on Cununurra clay. Sites Cum55-1 and Cum55-2 were located in block 55 at Cummings farm, which in 2004–05 had a sugarcane crop grown on Cununurra clay. Soil samples were collected at 10-cm depth intervals at 3 or 4 times within the annual growing season of the crops.
APPENDIX H

Soil moisture and lithology logs from piezometer drill holes at KTC plantation

Description:
Piezometer locations are indicated on Figure 18.

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**CO39**

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</table>

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**Project:** ORIA Groundwater Drainage and Evaluation  
**Location:** Kununurra, Western Australia  
**Drilled Date:** 29.08.06 to 03.09.06  
**Drilling Method:** 6” rotary auger  
**Coring Method:** Acrylic tube  
**Installation:** Piezometer, 50 mm PVC

**Drilled by:** Wayne Hick, Ross Galbraith  
**Logged by:** Tony Smith
CO40

Depth below ground | Core Samples | Gravimetric Soil Moisture (%) | Moisture Log | Lithology Log | Texture | Completion

0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 | 15

Very stiff | Very stiff | Clay | Clay | Clay
Dry | Slightly dusty | As above | Clay | Clay | Clay | Clay | Clay | Clay | Clay | Clay | Clay

As above | As above | Dusty and powdery | Saturated at bottom | Saturation, drilling water added | GRAVELY-CLAY | GRAVELY-CLAY

Bentonite | Cuttings | Gravel

Project: ORIA Groundwater Drainage and Evaluation
Location: Kununurra, Western Australia
Drilled Date: 29.08.06 to 03.09.06
Drilling Method: 6" rotary auger
Coring Method: Acrylic tube
Installation: Piezometer, 50 mm PVC

Drilled by: Wayne Hick, Ross Galbraith
Logged by: Tony Smith
APPENDIX I

Stabilised watertable drawdown induced by groundwater pumping from gravel beds beneath Ivanhoe Plain

Description:
This figure was reproduced from Smith et al. (2005). Stabilised watertable drawdown was reached after approximately two months of pumping at average rates of approximately 5,100 kL d\(^{-1}\) from well 10/00 and 4,900 kL d\(^{-1}\) from well 11/00. Pumping well 10/00 is located approximately 2 km northwest of KTC plantation.
APPENDIX J

Spectral analysis of piezometer water level records from KTC plantation, Scott Tree Farm and Mock Farm

Description:

The table below summarises the results of spectral analysis of the piezometer water level records from KTC plantation, Scott Tree farm and Mock Farm. Graphical results for each piezometer are presented following. Missing water levels records in the times series were filled by linear interpolation prior to spectral analysis.

All Fast Fourier Transforms (FFTs) and FFT filters were performed using the software package OriginLab, with following settings:

- Unit of time days (d)
- Selected time-series records of 1024 ($2^{10}$) or 512 ($2^9$) consecutive water level values at interval 0.0833 d (2 hr) or 0.0417 (1 hr)
- Cut-off frequency 0.667 d$^{-1}$ (period 1.5 d) for FFT low-pass and high-pass filters.

Results in the table are plotted in Figure 29 of the main report.

---

9 Origin 7 SR4 v7.0552(B552) http://www.OriginLab.com
<table>
<thead>
<tr>
<th>Piezometer</th>
<th>Tidal component</th>
<th>Diurnal spectral power from FFT</th>
<th>Semi-diurnal spectral power from FFT</th>
<th>Power spectral ratio (diurnal / semi-diurnal)</th>
<th>Water-table depth below ground surface, m</th>
<th>Lithology, dbgl</th>
</tr>
</thead>
<tbody>
<tr>
<td>CC38</td>
<td>P₁, S₂</td>
<td>9.895E-08</td>
<td>9.037E-08</td>
<td>1.036</td>
<td>3</td>
<td>silty clay, 0–7 m</td>
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<tr>
<td>CC39</td>
<td>P₁, S₂</td>
<td>7.102E-03</td>
<td>2.794E-03</td>
<td>2.542</td>
<td>5</td>
<td>clay, 0–3 m</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>clayey sand, 3–3.5 m</td>
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<tr>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>gravelly sand, 3.5–7 m</td>
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<td>clayey sand, 7–8.5 m</td>
</tr>
<tr>
<td>CC40</td>
<td>P₁, S₂</td>
<td>5.679E-03</td>
<td>5.672E-04</td>
<td>10.012</td>
<td>7</td>
<td>clay, 0–7.5 m</td>
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<td>gravelly clay, 7.5–10 m</td>
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<td>CC41</td>
<td>P₁, S₂</td>
<td>9.442E-04</td>
<td>1.452E-04</td>
<td>6.503</td>
<td>7</td>
<td>clay, 0–2.5 m</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>clayey sand, 2.5–3 m</td>
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<tr>
<td></td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>sand, 3–3.8 m</td>
</tr>
<tr>
<td>CC42</td>
<td>P₁, S₂</td>
<td>8.807E-03</td>
<td>1.080E-03</td>
<td>8.247</td>
<td>6</td>
<td>clay, 0–6.5 m</td>
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<td>sandy clay, 5.5–8.5</td>
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<tr>
<td>CC49</td>
<td>P₁, S₂</td>
<td>6.775E-04</td>
<td>1.061E-03</td>
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<td>clay, 0–13 m</td>
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<tr>
<td>CC50</td>
<td>P₁, S₂</td>
<td>5.000E-03</td>
<td>9.292E-03</td>
<td>0.547</td>
<td>5</td>
<td>clay, 0–7 m</td>
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<tr>
<td>CC51</td>
<td>P₁, S₂</td>
<td>3.399E-04</td>
<td>1.035E-04</td>
<td>3.284</td>
<td>3–4.5</td>
<td>clay, 0–7 m</td>
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<tr>
<td>CC52</td>
<td>P₁, S₂</td>
<td>1.897E-03</td>
<td>5.199E-03</td>
<td>0.365</td>
<td>6.5</td>
<td>clay, 0–7 m</td>
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<tr>
<td>CC54</td>
<td>P₁, S₂</td>
<td>2.158E-04</td>
<td>1.262E-04</td>
<td>1.710</td>
<td>8</td>
<td>clay, 0–4 m</td>
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<td></td>
<td>clayey sand, 4–7 m</td>
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<td></td>
<td></td>
<td></td>
<td>sand, 7–10 m</td>
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<tr>
<td>CC56</td>
<td>P₁, S₂</td>
<td>1.121E-02</td>
<td>1.447E-03</td>
<td>7.747</td>
<td>7.5</td>
<td>clay, 0–6.5 m</td>
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<td>clayey sand, 5.5–8.5 m</td>
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<tr>
<td>CC56</td>
<td>P₁, S₂</td>
<td>6.896E-04</td>
<td>9.568E-04</td>
<td>0.719</td>
<td>7.5</td>
<td>clay, 0–4 m</td>
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<td></td>
<td></td>
<td></td>
<td>silty sand, 4–5.5 m</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>sand, 5–6.5 m</td>
</tr>
<tr>
<td>CC57</td>
<td>S₂</td>
<td>5.987E-06</td>
<td>9.952E-05</td>
<td>0.070</td>
<td>5</td>
<td>sandy clay, 0–1 m</td>
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<tr>
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<td></td>
<td></td>
<td></td>
<td></td>
<td>sand, 1–4 m</td>
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<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>gravelly sand, 4–7 m</td>
</tr>
<tr>
<td>CC59</td>
<td>P₁, S₂</td>
<td>1.821E-03</td>
<td>4.415E-03</td>
<td>0.412</td>
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<td>clay, 0–10 m</td>
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<tr>
<td>CC34</td>
<td>P₁, S₂</td>
<td>1.335E-02</td>
<td>9.063E-04</td>
<td>14.730</td>
<td>1–4.5</td>
<td>sandy clay, 0–5.5 m</td>
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<tr>
<td>CC36</td>
<td>P₁, S₂</td>
<td>1.187E-02</td>
<td>1.495E-02</td>
<td>0.794</td>
<td>1–2.5</td>
<td>sandy clay, 0–3.8 m</td>
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<tr>
<td>CC46</td>
<td>P₁, S₂</td>
<td>7.996E-03</td>
<td>8.398E-03</td>
<td>0.916</td>
<td>0–1.5</td>
<td>clay, 0–3.8 m</td>
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</table>

P₁ is the solar diurnal constituent with period 1.0027 d and frequency 0.9973 1d⁻¹
S₂ is the principal solar semi-diurnal constituent with period 0.5 d and frequency 2.0 1d⁻¹
CO34: spectral analysis

[Graph showing water level over time with annotations for CO34, FFT low-pass filter (1.5-d period), and FFT high-pass filter (1.5-d period)]

CO34: drilling photo

[Image of a drilling site with a truck and equipment, labeled as CO34 drilling photo]
CO36: spectral analysis

![Spectral analysis diagram](image)

CO36: drilling photo

![Drilling photo](image)
CO38: spectral analysis

![Spectral analysis graph showing water level changes over time.](image)

(a) Fast Fourier Transform

(b) Data from CO38, FFT Low-pass filter (1.5-d period), and FFT High-pass filter (1.5-d period)

CO38: drilling photo

![Drilling site image](image)
CO39: spectral analysis

![Spectral analysis graph showing water level and frequency analysis]

CO39: drilling photo

![Drilling site photo with trees and equipment]

Trees and groundwater in the ORIA
CO40: spectral analysis

CO40: drilling photo
CO41: spectral analysis

![Graph showing water level over time with FFT analysis]

CO41: drilling photo

![Image of drilling equipment in a forested area]
CO42: spectral analysis

![Spectral Analysis Chart]

CO42: drilling photo

![Drilling Photo]
CO45: spectral analysis

![Spectral analysis graph with wave patterns and frequency data.]

CO45: drilling photo

![Drilling photo showing the drilling process and equipment.]
CO49: spectral analysis

![Graph showing water level over time with frequency analysis](image)

CO49: drilling photo

![Drilling site with equipment](image)
CO50: spectral analysis

![Water Level Plot](image1)

![Fast Fourier Transform](image2)

CO50: drilling photo

![Drilling Photo](image3)
CO51: spectral analysis

CO51: drilling photo
CO52: spectral analysis

![Graph showing water level fluctuations over time](image)

CO52: drilling photo

![Drilling operation in a forested area](image)
CO54: spectral analysis

![Graph showing water level and frequency analysis](image)

**CO54: drilling photo**
(No photograph taken)
CO55: spectral analysis

![Graph showing water level and frequency analysis](image1)

CO55: drilling photo

![Drilling site with equipment and personnel](image2)
CO56: spectral analysis

CO56: drilling photo
CO57: spectral analysis

[Graph showing water level over time with frequency and power analysis]

CO57: drilling photo

[Drilling site photo with equipment and environment]
CO59: spectral analysis

![Graph showing water level over time with different frequency components identified.]

CO59: drilling photo

![Drilling site with equipment and surroundings.]

Trees and groundwater in the ORIA
APPENDIX K

Water balance at KTC plantation, Scott Tree Farm and Mock Farm for entire duration of the study, August 2006 to April 2008

<table>
<thead>
<tr>
<th>Water balance element, mm</th>
<th>KTCW</th>
<th>KTCE</th>
<th>KTC Integrated</th>
<th>Scott</th>
<th>Mock</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. FAO56 reference evapotranspiration</td>
<td>3595</td>
<td>3595</td>
<td>3595</td>
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<tr>
<td>2. Rainfall</td>
<td>1703</td>
<td>1703</td>
<td>1703</td>
<td>1439</td>
<td>1701</td>
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<tr>
<td>3. Rainfall interception</td>
<td>426</td>
<td>255</td>
<td>375</td>
<td>144</td>
<td>340</td>
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<tr>
<td>4. Rainfall runoff</td>
<td>90</td>
<td>175</td>
<td>116</td>
<td>260</td>
<td>90</td>
</tr>
<tr>
<td>5. Effective rainfall</td>
<td>1187</td>
<td>1273</td>
<td>1213</td>
<td>1035</td>
<td>1271</td>
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<td>6. Effective irrigation</td>
<td>250</td>
<td>100</td>
<td>205</td>
<td>600</td>
<td>150</td>
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<tr>
<td>7. Rainfall - runoff + irrigation (2-4+6)</td>
<td>1863</td>
<td>1628</td>
<td>1793</td>
<td>1779</td>
<td>1761</td>
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<td>8. Tree transpiration</td>
<td>1428</td>
<td>655</td>
<td>1196</td>
<td>545</td>
<td>837</td>
</tr>
<tr>
<td>9. Soil evaporation</td>
<td>175</td>
<td>263</td>
<td>201</td>
<td>350</td>
<td>175</td>
</tr>
<tr>
<td>10. Evapotranspiration (3+8+9)</td>
<td>2029</td>
<td>1173</td>
<td>1772</td>
<td>1039</td>
<td>1352</td>
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<tr>
<td>Water balance (7-10)</td>
<td>-166</td>
<td>455</td>
<td>20</td>
<td>740</td>
<td>409</td>
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</tbody>
</table>
APPENDIX L

Relationship between diameter at breast height (Dbh) and sapwood area for African mahogany, sandalwood and other host species (Cathormium, teak and wattle)

Description:
Data was pooled for the KTCW, KTCE, Scott Tree Farm and Mock Farm.

\[
y = 0.3826x^{2.1061} \\
R^2 = 0.9222
\]

\[
y = 2.7755x^{1.2391} \\
R^2 = 0.9396
\]

\[
y = 0.9688x^{1.8} \\
R^2 = 0.9232
\]
**APPENDIX M**

Average basic density (volume measured by displacement of water) and water content of sapwood cores sampled during June 2007 and May 2008 at KTC plantation, Scott Tree Farm and Mock Farm

<table>
<thead>
<tr>
<th></th>
<th>Sapwood Basic Density, g dry weight per cm³</th>
<th>Sapwood Water Content, g H₂O per g dry sapwood</th>
</tr>
</thead>
<tbody>
<tr>
<td>KTCW</td>
<td>0.69</td>
<td>0.58</td>
</tr>
<tr>
<td>KTCE</td>
<td>0.69</td>
<td>0.53</td>
</tr>
<tr>
<td>Scott sandalwood</td>
<td>0.74</td>
<td>0.49</td>
</tr>
<tr>
<td>Scott teak</td>
<td>0.58</td>
<td>0.88</td>
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<td>Scott cathormium</td>
<td>0.54</td>
<td>0.98</td>
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<tr>
<td>Mock sandalwood</td>
<td>0.69</td>
<td>0.40</td>
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<td>Mock cathormium</td>
<td>0.59</td>
<td>0.64</td>
</tr>
<tr>
<td>Mock wattle</td>
<td>0.63</td>
<td>0.44</td>
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<tr>
<td>Mock mahogany</td>
<td>0.66</td>
<td>0.44</td>
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</table>