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Predicting the water-use of Eucalyptus nitens plantations in Tasmania using a Forest Estate Model

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Predicting the water-use of *Eucalyptus nitens* plantations in Tasmania using a Forest Estate Model

Prepared for

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by

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Executive Summary

The objective of this project was to use a forest estate model to predict the annual water-use of *Eucalyptus nitens* plantations. This report describes measurements of water-use made in *E. nitens* plantations in Tasmania, the development of a model to predict water-use of *E. nitens* plantations and incorporation of this model in an estate model.

An estate model that includes predicted water-use will enable forest managers to simultaneously assess the impacts of plantation management decisions on wood production, income and water-use. This capacity will be useful in limiting the impacts of plantation management on other water-users, ecosystems or threatened species, while maximising wood production and profits.

Water-use was measured in 5 *E. nitens* plantations in the Florentine Valley, Tasmania from 2008 to 2010, and in 1 plantation at Forestier during 2011. Plantations in the Florentine Valley were aged 9, 7, 4 and <1 year at the start of the experiment. Some plantations were thinned, some were pruned, and some were treated for insect pests in accordance with standard management procedures. In the Florentine Valley, rainfall averages 1200 mm/yr, potential evaporation averages 930 mm/yr, and the soils are well-drained red/brown ferrosols. The plantation at Forestier was 6 years old at the time of the experiment, and is at a location that experiences average rainfall of 700 mm/yr, on well drained Jurassic dolerite soil, where boulders and cobbles are common. This plantation was not thinned or pruned.

Water-use (also called evapotranspiration or interception) was defined as the sum of transpiration, canopy interception and soil evaporation. Transpiration was measured using sapflow sensors, canopy interception was determined from throughfall troughs and stemflow collection, and soil evaporation was measured with mini-lysimeters.

Periodic surveys of stem diameter at 1.3 m for plots of trees in an area of known size in each plantation were used to calculate plot basal area.

Water-use depended on the age and basal area of the plantation and was also influenced by rainfall in the year of measurement. Water-use of plantations in the Florentine ranged from 544 mm/yr in a 1-year-old plantation to 1052 mm/yr for an unthinned 9-year-old plantation. Thinning reduced plantation water-use by up to 30%. Water-use of the Forestier plantation was 752 mm/yr.

Predictions from existing models of plantation growth and water-use were compared to the measurements. ProMod provided the best prediction of basal area growth for the plantations using site parameters as input data, but water-use was provided as an average for plantations older than 3 years, not for individual growth years. If annual water-use was provided as a ProMod output it could possibly be used to test or develop basal area: water-use functions for a wide range of locations. CABALA overestimated basal area and water-use for the Florentine Valley plantations. CABALA shows promise for developing basal area: water-use functions for a wide range of locations, but needs further calibration for *E. nitens*.

A simple empirical model (below) was developed from the Florentine field data to predict annual water-use of *E. nitens* using plot basal area and annual rainfall. The adjusted R-squared statistic indicates that the model explains 79% of the variability in water-use.

Water-use (mm/yr) = 149 + 11.0*Basal Area (m^2/ha) +0.361*Rainfall (mm/yr)

The water-use measured at Forestier (792 mm), where rainfall was 854 mm and basal area was 30.2 m^2/ha, fell within the 95% prediction interval (607 to 974 mm) for the model (above). The model predicted Forestier water-use of 790 mm, which provides some confidence that the Florentine model can be used at this location, and may be applicable for use elsewhere in Tasmania.

The empirical model was successfully included in Forestry Tasmania's Forest Estate Model (FEM). The FEM was used to generate estimates of water-use, the wood volume available to cut, and standing basal area for 1532 ha of *E. nitens* plantation in the Florentine Valley over a 90 year period. The FEM showed that managing plantations to produce smooth water-use and smooth wood production is compatible – managing for one produces the other. This lends further support to the concept of a regulated forest minimising changes to hydrological systems (Hennes et al., 1971).

The methods used to measure water-use and build the empirical water-use model are readily transferable to other plantation species and native forests. Managers of other plantation and forest types typically have FEMs and it is likely that with the collection of some additional data and use of process models that they could use similar methods to develop simple empirical models of water-use for the species and environments that they manage.

The difference between rainfall and water-use represents the amount of water that is available either as streamflow or groundwater. Where forest management increases water-use, it can be deduced that there will be a reduction in water available either as streamflow or groundwater. This would give plantation (and forest managers) the power to consider plantation water-use and its affect on water availability during decision making processes.

Further water-use studies could be undertaken in gauged catchments if a greater understanding is required of the relationship between water-use and streamflow, however, it is likely that this relationship will vary markedly between catchments based on their size, geology, topography, the mix of land uses, weather and rainfall patterns, and as such any relationships may not be readily transferable between sites.

Contents

1. Introduction

Plantation development can result in changes to the availability of water (either as streamflow or in groundwater). Where grassland is planted with trees, water availability can decrease (Bosch and Hewlett, 1982: Vertessy, 2001: Bren et al., 2006: Best et al, 2003). Where forest is replaced with plantation there can be changes in water availability in either direction (Bren and Hopmans, 2007: Bren et al., 2006: Cornish and Vertessy, 2001). The changes in water availability are linked to changes in the capacity of vegetation to use water.

In this paper, water-use is the term used to describe the total amount of water evaporated from an area of plantation due to transpiration, canopy interception and soil evaporation. However, it is common for other authors to use the terms evapotranspiration or interception to describe water-use. Water availability is the term used in this paper to describe the difference between rainfall and water-use. Available water either becomes streamflow, or moves into and through soil or aquifers. Other authors may refer to water availability as water yield or describe its components.

In regions of Australia where water resources are in limited supply or where there is concern that aquatic, riparian or groundwater ecosystems could be impacted by reduced water availability, water licensing, codes of practice, regulations and policy have been developed to preserve water resources. These codes and regulations may limit plantation development or make it more expensive.

The National Water Initiative represents an agreement by governments across Australia to achieve a more cohesive approach to the way Australia manages, measures, plans for, prices, and trades water (Council of Australian Governments, 2005). The National Water Initiative gives governments the power to manage interception by plantations either by limiting their development or by issuing water licences.

In South Australia, the State government has policies to limit plantation development in some locations or to issue water licences to protect groundwater resources (Department for Water, 2012). In some states, Forestry regulators and Codes of Forest Practice limit the extent of forest and plantation activity in some catchments. For example, catchments contributing to council or domestic water supplies, or catchments with threatened aquatic species, may have limits on the area of plantation developed during a nominated period (Forest Practices Board, 2000).

In rare cases, plantation development has been prevented by legal action from neighbours who fear that local surface and groundwater resources would be compromised by plantation development (e.g. Forest Practices Tribunal, 2009 - Clement v FPA and Curran, 2009).

Restrictions on plantation development or a requirement to purchase water licences ultimately lead to greater costs for industry through greater dispersion of the plantation estate or through the purchase of water licences.

It is important that water-use by plantations can be quantified and predicted so that catchment managers, water authorities and natural resource managers can ensure that water supplies, licensed allocations, threatened species, ecosystems and aquaculture are not compromised; so that forest managers can avoid unwanted impacts on water while continuing to produce wood; and so that regulators can develop and implement fair regulations and policies.

State agencies and water management authorities are considering how to account for and manage water use by plantations but the methods used to do this mostly require further development. The State Government of Victoria plans to use the Department of Primary Industries Land Use Information System to model the water use of different land uses based on previous studies of evapotranspiration, streamflow and groundwater (Department of Sustainability and Environment, 2011). South Australia uses an "annualised deemed value" for plantation water consumption to allocate licenses and identify plantation development thresholds (Harvey, 2009). This smoothes hydrologic impact over the full forest rotation period and expresses impacts as an annualised value for the full rotation of all plantations of the same species in the same groundwater management area. The Department of Primary Industries, Parks, Water and Environment in Tasmania have included plantation water use in some of their streamflow models by incorporating the TasLUCaS plantation streamflow change equation (Brown et al., 2006; Hydro Tasmania Consulting, 2007). The Tasmanian streamflow models are currently used to determine which catchments may have significant impacts from plantation development.

Plantation owners have attempted to understand the impacts of plantations on water resources through paired catchment experiments (Cornish and Vertessy, 2001; Bren and Hopmans, 2007), water use studies (Forrester et al., 2010; Hatton and Vertessy, 1990; McJannet et al., 2000; Feikema et al., 2007; Benyon and Doody, 2004) and process models such as 3PG, CABALA (Battaglia et al., 2004), and Promod (Sands et al., 2000). While there is a general understanding of the direction and magnitude of water use or streamflow change associated with plantation development in some locations as a result of these studies, the development and implementation of tools that enable plantation owners to assess impacts of plantations and plan activities to minimise negative outcomes for water resources is ongoing.

To quantify, predict and manage water-use by plantations, Forestry Tasmania commenced a program of research in 2007. The objective of the research was to develop a tool that enables assessment of plantation water-use during the wood-flow planning process. Early in the research program Forestry Tasmania's Forest Estate Model (FEM) was identified as a tool that could be developed for water management. The FEM currently uses information on the location, type, management and growth of plantations to predict wood-flow. By including simple empirical plantation water-use functions in the FEM it would be able to simultaneously assess water-use and wood production, and explore different harvest and planting schedules to optimise wood production and/or water availability.

Previous studies provide evidence of links between forest and plantation water use and growth parameters such as sapwood area, leaf area and basal area (Macfarlane et al., 2010; Forrester et al., 2010; Roberts et al., 2001; Vertessy et al., 2001). Creating plantation water-use functions based on growth parameters for use in the FEM requires further collection of site and species specific water-use and growth data, evaluation of existing growth and water-use models, and use of previously published data. Forestry Tasmania chose to focus on developing a function for *Eucalyptus nitens* plantations in Tasmania – this being a widely planted species for which limited water-use information was available, and an ideal candidate for a pilot study given the uniform plantation stand structure.

This report describes *E. nitens* water-use experiments conducted at two locations in Tasmania; the Florentine Valley, where water-use was measured in 5 plantations over a 3 year period, and at Forestier, a drier site on the Tasman Peninsula, where water-use was measured in 1 plantation over a 1 year period.

The experimental methods were described in Roberts and Barton-Johnson (2009). Much of the inspiration for the experimental methods came from Roberts (2001), Roberts et al. (2001), Benyon and Doody (2004), and Putuhena and Cordery (1996).

The results of the Florentine water-use study were published in Roberts (2011A). A summary of the most important results from the Florentine study is provided in Roberts (2011A). A description of the Forestier plantation and the results of the Forestier study are provided in this report as they are not published elsewhere. Evaluation of existing models was described by Roberts (2011). Updated comparisons of two models, ProMod and CABALA, are presented in this report.

The process of developing the *E. nitens* water-use function for the FEM is described in this report. Examples are provided of the outputs from the FEM when the water-use function derived from the experiments is included.

2. Florentine Study Summary

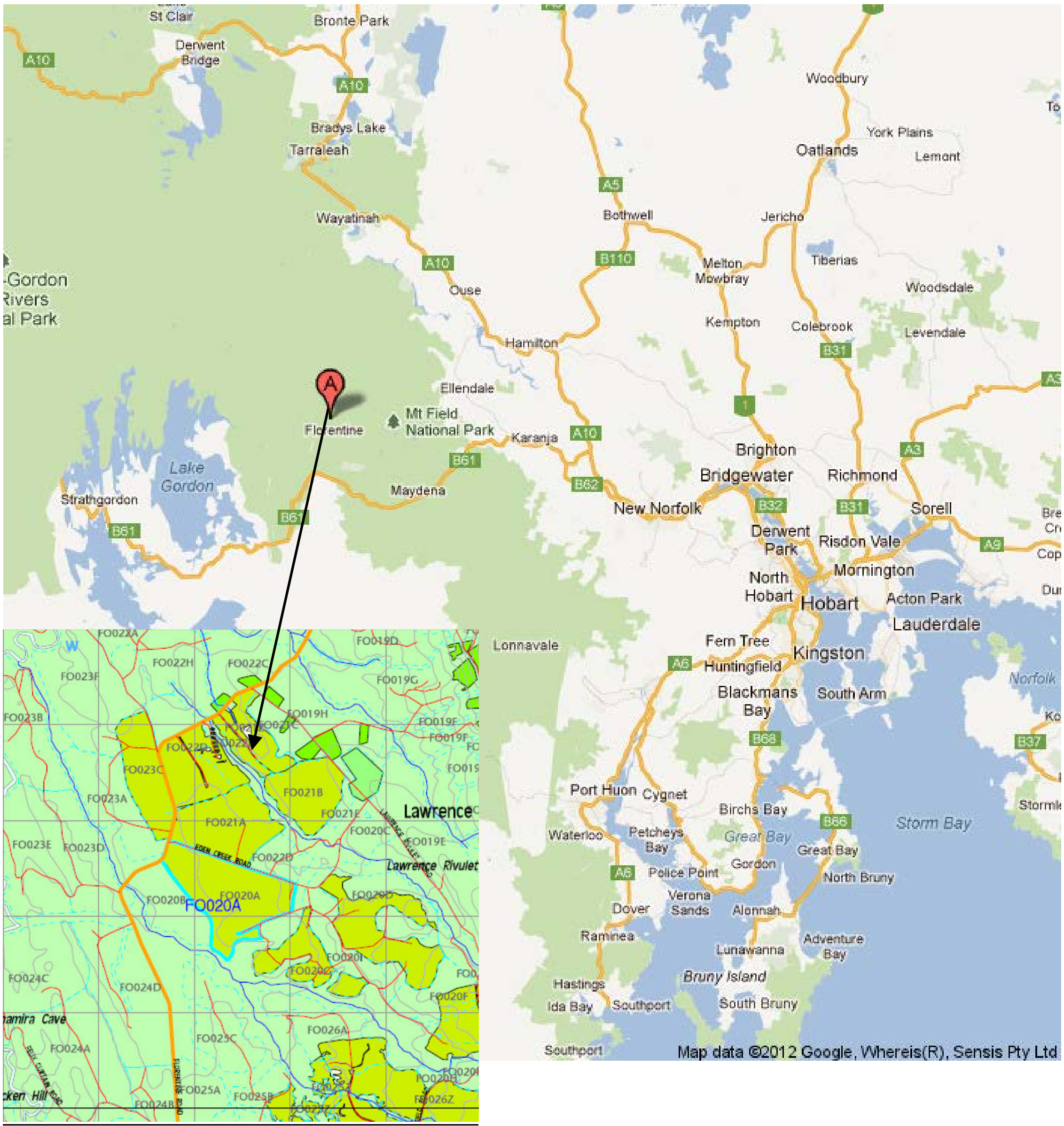

Figure 1. Location of Florentine study sites (Source - Google Maps and Forestry Tasmania GIS)

Water-use and its constituent processes (transpiration, canopy interception and soil evaporation) were measured in five *E. nitens* plantations of different age (Table 1) situated close to each other in the Florentine Valley (Figure 1) in Tasmania from 2008 to 2010. The plantations occur at 375-425 m above sea level on Jurassic dolerite with some limestone outcrops. The soils are deep well-drained red/brown ferrosols (Grant et al., 1995). Annual rainfall in the Florentine Valley was between 984 and 1425 mm during the experiment; the long-term average rainfall at the nearest weather station is 1200 mm/yr (Maydena, Bureau of Meteorology). Potential evaporation (Silo Data Drill, QLD DERM) ranged between 887 and

975 mm/yr during the experiment. The ratios of rainfall to potential evaporation suggest that the site is seasonally water-limited but anecdotal evidence suggests that, during dry summer periods, the trees have access to ground water, and that their overall annual water-use is consistent with that of plantations growing on a non-water-limited site. Roberts (2011A) provides a full description of the plantations and the results from this experiment.

Estimates of annual and monthly basal area, canopy interception, soil evaporation and transpiration were made during the study (Roberts, 2011). The purpose of these estimates was to generate estimates of annual water-use for adjacent plantations of different age and basal area, with a view to developing water-use functions that could be used in the FEM. Only annual data are shown in this report as this is the temporal scale of the FEM. Data could be disaggregated to smaller time intervals if they were required for other uses.

The amount of water-used by the plantations, and the proportions of this total used by the different water-use processes (transpiration, canopy interception and soil evaporation), varied with age (Figure 2). Figure 2 shows the annual canopy interception, soil evaporation and transpiration associated with each plantation for each year, and the thinning status of the plantation.

In a plantation less than 1-year-old, soil evaporation was the dominant process, accounting for 376 mm/yr, while transpiration and canopy interception combined only accounted for 168 mm/yr. In an 11-year-old unthinned plantation, transpiration (445 mm/yr) and canopy interception (379 mm/yr) were the dominant processes, with soil evaporation just 40 mm/yr. Thinning reduced canopy interception and transpiration, from around 1000 mm/yr in an unthinned stand to around 660 mm/yr, while markedly increasing soil evaporation, from an unthinned value of around 40 mm/yr to a thinned value of 120-200 mm/yr.

Annual water-use was thus linked to the age of unthinned plantations (R^2=0.68; Figure 3), and also thinning status (Figure 3). The thinned data set doesn't span enough years to allow analysis over time.

In 2010 all plantations recorded lower than anticipated water-use. This is probably because lower than average rainfall (984 mm) and lower than average potential evaporation (887 mm) occurred in 2010. Some of the variation in the relationship between annual water-use and age thus appears to be due to environmental conditions experienced during the year of measurement. Water-use of plantations of the same age could therefore vary between years.

Furthermore, plantation growth is also a function of the conditions experienced throughout the entire life-cycle of the plantation, and some plantations originated during periods with better conditions than others and hence had greater density, leaf area and/or basal area for a given age. Thus, unthinned Plantation 20A had lower water-use in 2008 than younger and older unthinned plantations in that year, which may indicate that this plantation has a lower leaf area or growth rate than other plantations due either to site quality or the conditions experienced in its early life.

Table 1. Plot information for *E. nitens* plantations in Florentine Valley

Coupe ID	*FO021AC*	*FO021AT*	*FO020A*	*FO023C*	*FO022D*
Eucalypt Species	*E. nitens*	*E. nitens*	*E. nitens*	*E. nitens*	*E. nitens*
Date Planted	08/1999	08/1999	08/2001	05/2004	10/2007
Coupe size (ha)	60	60	82	44	56
Mean annual increment (m^3/ha)	27	27	24	26	25
Experimental Plot Area (m^2)	910	815	1104	1075	864
Number of trees in plot (before and after thinning, where thinned)	96	86 / 27	125 / 47	110	120
Regime	EC3 High prune	EC3 High prune	EC3 High prune	EC3 High prune	EC2 Mid Prune
Easting	456323	456294	456366	455520	456102
Northing	5282925	5282934	5282070	5283350	5283431
Original stocking	1086	1086	1067	1100	1100
Date/s of pruning	1/4/05 8/2/07	1/4/05 8/2/07	1/3/06 18/12/06 1/2/08	15/5/08	unpruned
Dates of thinning	unthinned control	29/08/07	28/11/08	Plantation thinned, but research plot unthinned	unthinned
Pest control	24/12/03 28/11/05	24/12/03 28/11/05	24/12/03 28/11/05 30/12/07	24/12/08 30/12/07	

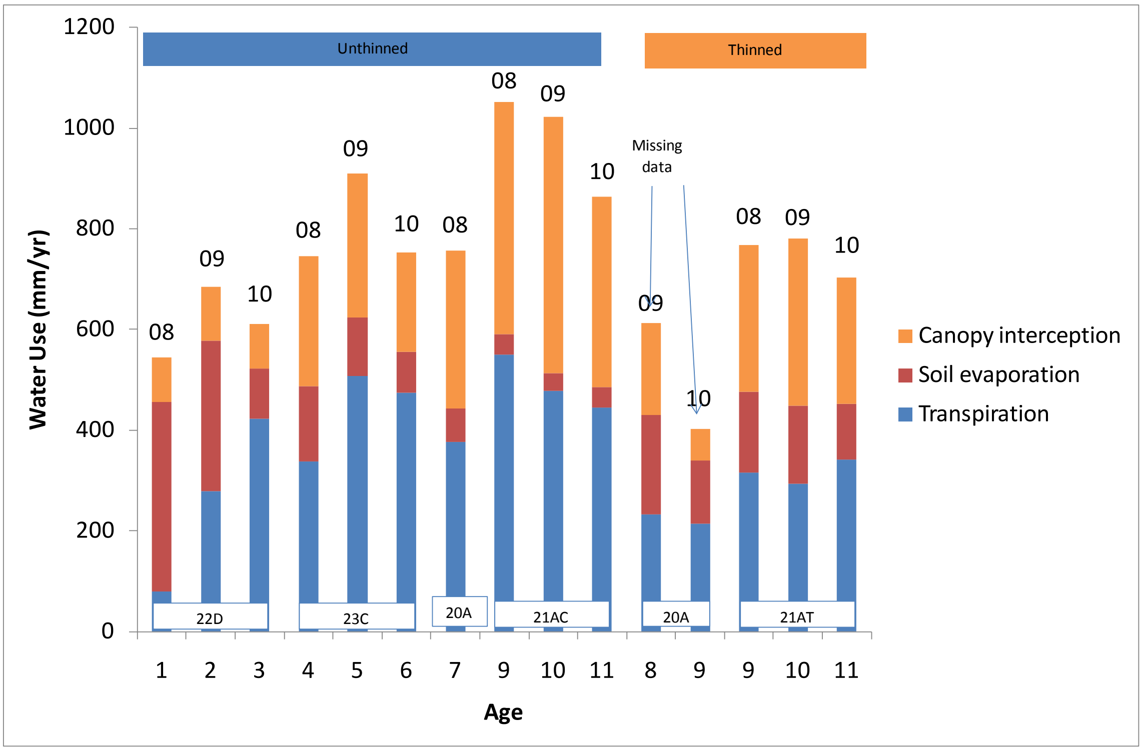

Figure 2. Annual canopy interception, soil evaporation and transpiration for each plantation, for each year of age, for thinned and unthinned plantations in the Florentine Valley. Numbers above each column are the calendar year of measurement. Numbers at the base of columns are coupe names.

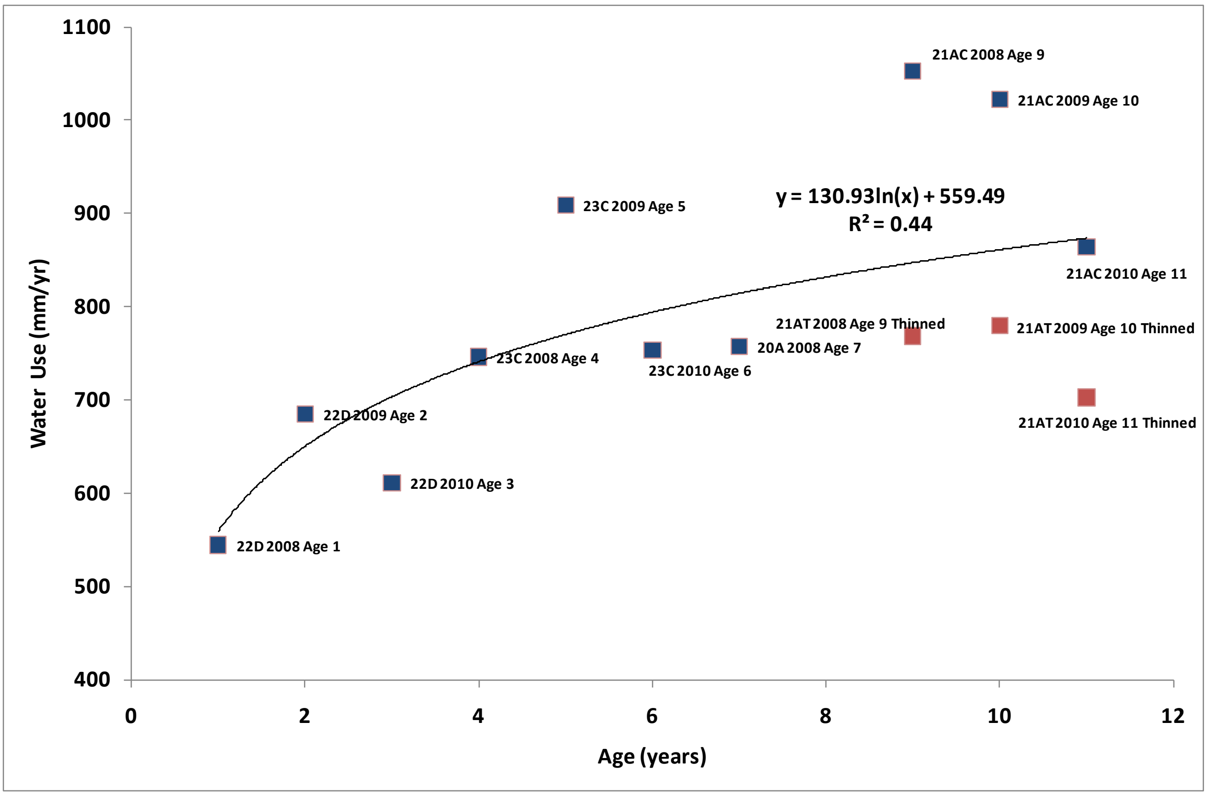

Figure 3. The relationship between age and annual water-use of plantations in the Florentine Valley. Blue squares represent unthinned plantations, red squares represent thinned plantations. Labels show plot ID, year of measurement and plantation age.

Age could be used to predict water-use in the FEM (Figure 3); however, stand basal area (Figure 4) was a better predictor of water-use than age.

Figure 4 shows the relationship between annual average basal area and annual total water-use for each plantation and year of the study – 2009 and 2010 data were missing for 20A thinned plots. There is a strong relationship between basal area and water-use (R^2=0.59).

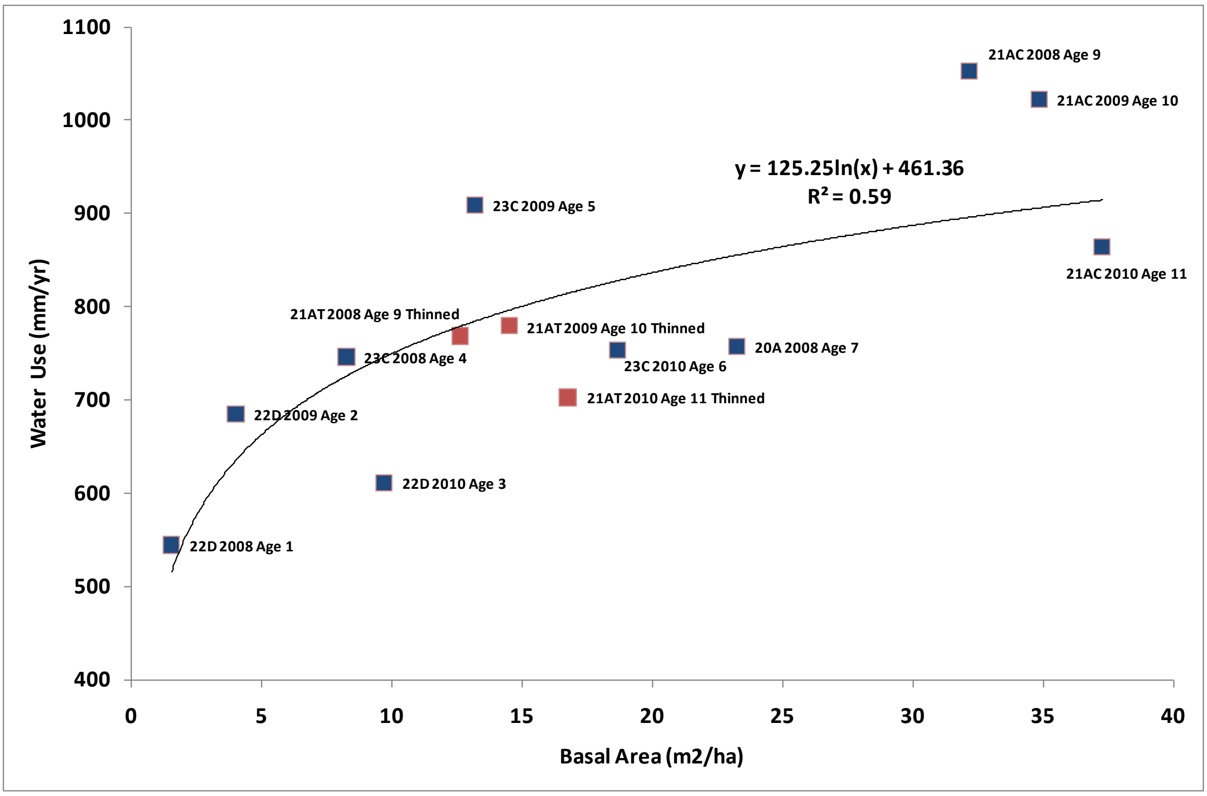

Figure 4. Relationship between basal area and water-use for thinned and unthinned plantations in the Florentine Valley. Labels show plot ID, year of measurement, age, and thinning status.

Mean error in the prediction of water-use from the basal area: water-use function of Figure 4 was 10% (Table 2), with errors ranging from 1 to 22% for individual plantations and years (mean absolute error of 76 mm, Statgraphics). The model residuals indicate that the function is a good fit to the data.

It is important to note that the basal area: water-use function (Figure 4) has an upper limit determined by potential evapotranspiration[1] (around 930 mm/yr), and a lower limit which represents the water-use of deforested land (around 500 mm/yr depending on weed/grass cover). It is likely that once the upper limit of water-use is achieved by a plantation, water-use will continue at this level while the plantation remains in good health.

The potential evaporation estimate for the Florentine Valley was obtained from Silo Data Drill and is calculated from air temperature, solar radiation and vapour pressure deficit data. Rayner (2006) concluded that the estimation method used by Silo Data Drill tends to underestimate solar radiation during windy conditions. It is likely that the annual potential evaporation estimate provided by Silo Data Drill is an underestimate for the site. This may explain why it was possible for measured water use to exceed 1000 mm/yr in the oldest unthinned plantation.

Table 2. Summary of results for model fitting.

Basal Area (m2/ha)	Water Use Actual (mm/yr)	Water Use Predicted (mm/yr)	Water Use Residual (Actual-Predicted)	Water Use Error (%)	Year
1.5	544.4	514.9	29.4	5.4	2008
4.0	684.8	635.1	49.7	7.3	2009
9.7	611.2	745.8	-134.7	22.0	2010
8.3	746.0	725.8	20.2	2.7	2008
13.2	909.1	784.5	124.5	13.7	2009
18.7	753.3	828.0	-74.7	9.9	2010
23.2	757.2	855.4	-98.2	13.0	2008
32.2	1052.2	896.1	156.2	14.8	2008
34.8	1022.2	906.1	116.1	11.4	2009
37.3	864.4	914.5	-50.1	5.8	2010
12.6	768.5	778.8	-10.3	1.3	2008
14.5	779.8	796.4	-16.6	2.1	2009
16.8	702.8	814.4	-111.6	15.9	2010
		Average Error		**9.6**	

[1] **Potential evapotranspiration** (**PET**) is the loss expected over a surface with no limitation of water. It is a function of the atmospheric demand which depends primarily on the energy available from net radiation, the humidity gradient in the lower atmosphere, wind speed and surface roughness (Beven, 2005) or, is a representation of the environmental demand for evapotranspiration and represents the evapotranspiration rate of a short green crop, completely shading the ground, of uniform height and with adequate water status in the soil profile. It is a reflection of the energy available to evaporate water, and of the wind available to transport the water vapour from the ground up into the lower atmosphere. Actual evapotranspiration is said to equal potential evapotranspiration when there is ample water (Wikipedia - http://en.wikipedia.org/wiki/Evapotranspiration).

The basal area: water-use function calculated for the Florentine stands (Figure 4) tends to overestimate water-use during years of low rainfall and underestimate water-use during years of high rainfall. Table 2 shows that in 2010, when rainfall was 983 mm, actual minus predicted water-use was always negative. In 2008 which had 1259 mm and 2009 which had 1425 mm of rain, actual minus predicted water-use was more likely to be positive.

A multiple linear regression using basal area (m^2/ha) and annual rainfall (mm/yr) was formed in Statgraphics to predict water-use (WU) (Equation 1). P values below 0.05 for the intercept, basal area (BA) and rainfall (R), and an R^2 of 0.82 compared to an R^2 of 0.59 for the regression using basal area alone (Figure 4), shows that the rainfall term is a useful addition to the function. Equation 1 reduces the estimate of mean absolute error to 50 mm in the WU estimate compared with 76 mm for Figure 4 (Statgraphics). The derived function is:

$WU = 149+11.0*BA+0.361*R$ Equation 1.

Including rainfall in the function improves its ability to predict WU, and means that average rainfall can be included in predictions of water-use, that a stochastic rainfall model could be linked to the FEM to assess the effect of rainfall variability on water-use predictions, and that the FEM could assess scenarios where rainfall is reduced or increased in response to climate change (although evaluating climate change impacts is challenging because changes in water-use due to higher atmospheric CO_2 concentrations are still unknown).

3. Forestier Plantation Water-use

A plantation water-use research site was established in a plantation at Forestier in February 2011 to measure transpiration, canopy interception and soil evaporation. Forestier was selected because it has lower rainfall and greater potential to experience water deficits than the Florentine Valley. A weather station was also established. The same measurement techniques were used as at the Florentine site (Roberts and Barton-Johnson, 2009).

Data were collected from Forestier to see if Equation 1, which was developed from Florentine Valley plantation water-use data, can be successfully applied to other locations.

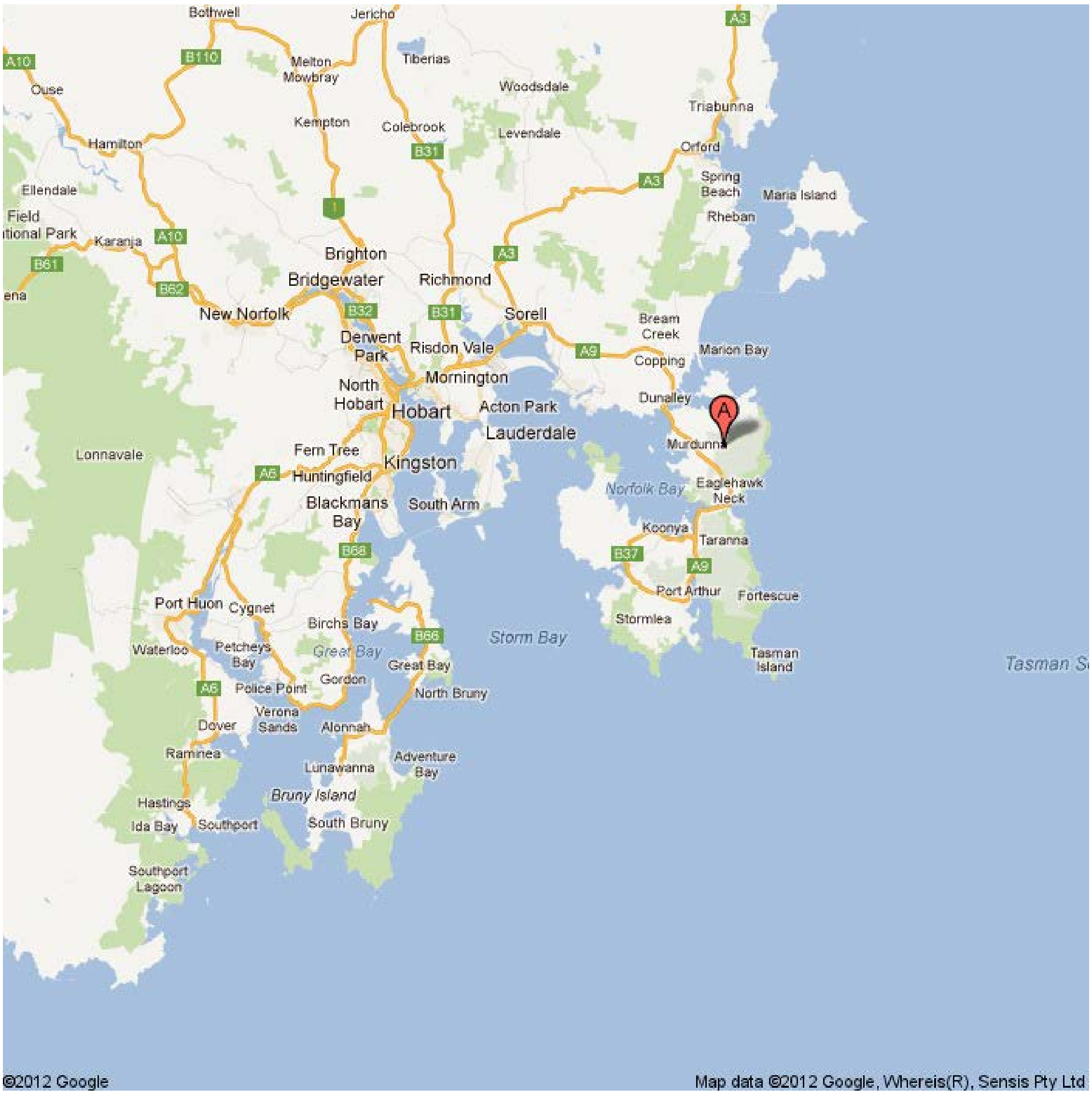

Figure 5. Location Map for Forestier research with "A" indicating research site location (Source- Google Maps)

3.1. Site description

The Forestier plantation is located near Hylands Rd, approximately 45 km east of Hobart (Easting 575,043, Northing 5,243,134) (Figure 5). The plantation research plot is approximately 270 m above sea level.

The *E. nitens* plantation was established in June 2005 at a density of 1117 stems per hectare. Spot cultivation was used to prepare the soil because the site is stony. The plantation is managed for pulp production and is not pruned or thinned, and there is no intention of these activities occurring in the future.

The research plot is underlain with Jurassic dolerite, and boulders and cobbles are common on the surface (30-80%), and in the soil matrix (50-90%). The soil is described as well drained, with moderate potential for erosion and low fertiliser requirement.

The nearest Bureau of Meteorology rain gauge is at Dunalley, approximately 6 km west of the site. Between 1974 and 2011, rainfall averaged 700 mm/yr at Dunalley, ranging from 511 to 1029 mm/yr. There is no distinct rainfall pattern in the monthly records. Most months average more than 50 mm of rainfall (Figure 6).

There are no local temperature data available – the nearest Bureau of Meteorology weather station is at Hobart airport, approximately 35 km to the west.

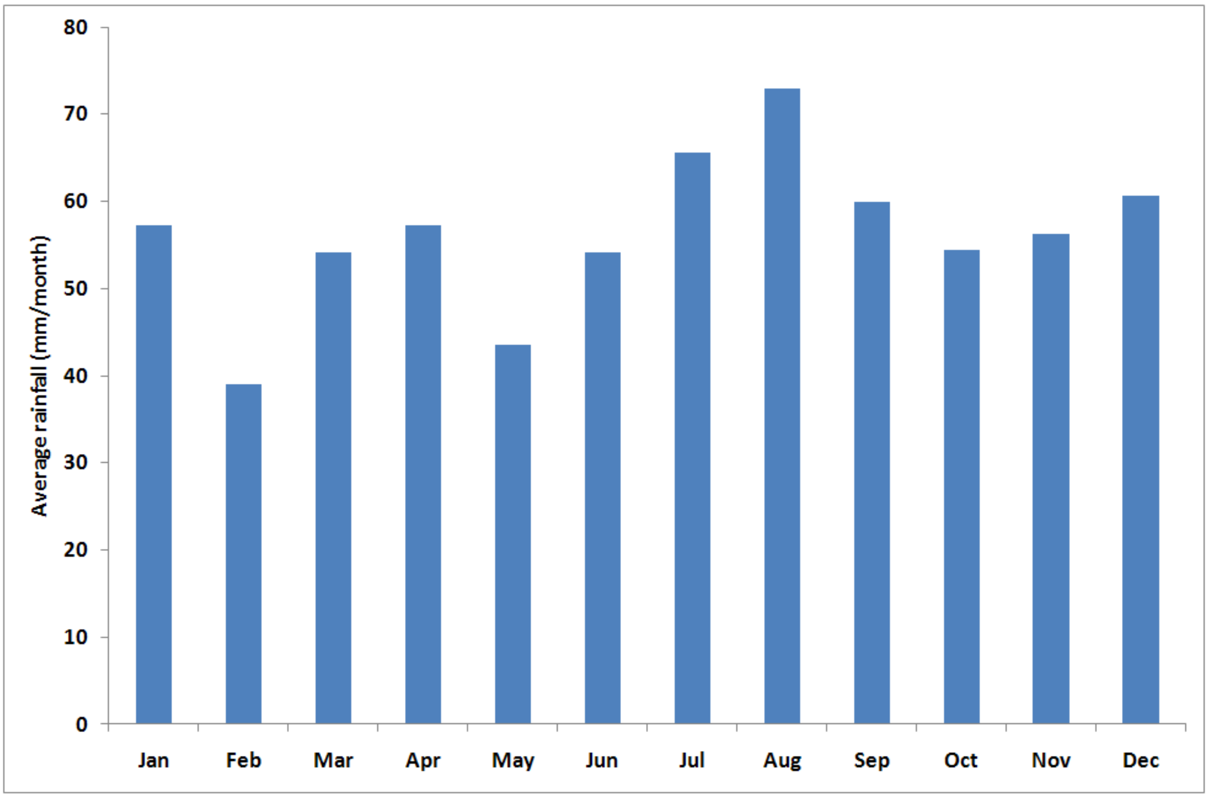

Figure 6. Average monthly rainfall at Dunalley between 1974 and 2011 (Bureau of Meteorology)

3.2. Weather Station

An automatic weather station was placed in a clearing adjacent to the research plantation. It recorded rainfall, air temperature, ground temperature, humidity, solar radiation, wind speed and direction. Data prior to May 2011 were lost due to technical difficulties. The tipping-bucket rain gauge recorded less rain than the bulk rain gauge (tipping bucket = 456 mm of rain between 7/5/2011 and 31/1/2012) and was deemed to be defective. The maximum temperature recorded was 29^{o} C, the minimum recorded was 0^{o} C.

3.3. Plantation basal area and sapwood area

A 20 m x 20 m (400 m^2) measurement plot containing 39 trees (some with multiple stems) was established on 26/2/2011. The diameter of every stem within the plot was measured at 1.3 m. Stems were remeasured on 20/6/2011, 19/10/2011 and 7/2/2012. Plot basal area grew from 29.27 m^2/ha on the 26/2/2011 to 32.52 m^2/ha on 7/2/2012.

Sapwood area was determined for a number of trees using an increment corer and assuming radial symmetry. Sapwood area was strongly correlated with basal area (R^2=0.78) for individual trees (Figure 7). Plot sapwood area was estimated at 10.75 m^2/ha at commencement and 11.77 m^2/ha at completion of the experiment.

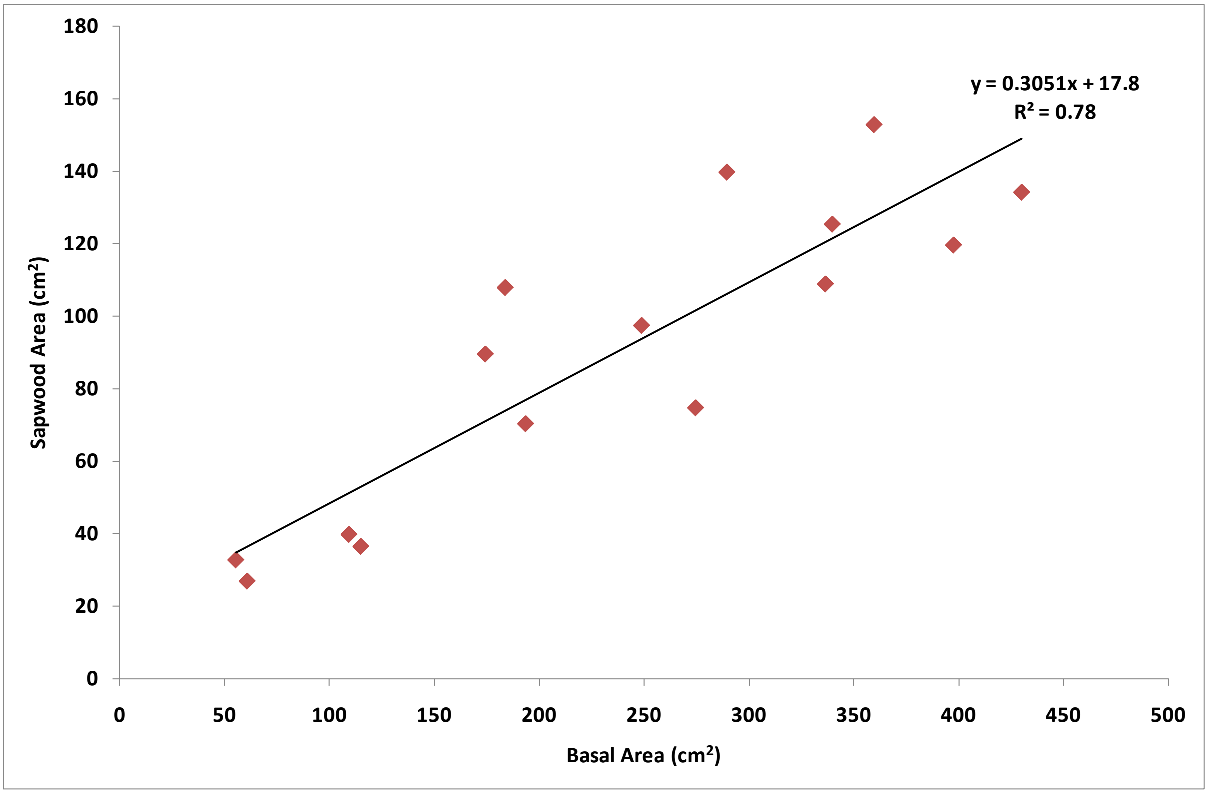

Figure 7. Relationship between stem basal area and stem sapwood area of *E. nitens* at Forestier

3.4. Instrumentation overview

Mini lysimeters and bulk rain gauges were placed beneath the canopy to determine soil evaporation. A throughfall trough was placed under the canopy and another was placed in a nearby clearing. Stem flow collectors were placed on three trees in the plot. A bulk rain gauge was placed in the clearing alongside the weather station and throughfall trough to verify the results from these. Heat pulse sensors were deployed to measure sap velocity in a subsample of stems.

3.5. Soil evaporation

Soil evaporation was measured with 10 mini lysimeters, and 10 rain gauges, each placed at random distances and bearings from a central point in the plot. The lysimeters were installed on 28/2/2011, and removed on 30/1/12 – a period of 11 months. During this time, an average of 96 mm of soil evaporation was measured from the lysimeters. Soil evaporation for the lysimeters was scaled to the year by assuming the evaporation from the missing month was equivalent to the average rate over the whole period of measurement – giving a total of 105 mm/year from the lysimeters. However, because approximately 50% of the plot soil surface is covered with boulders which do not allow evaporation, the soil evaporation of the plot was estimated at 52 mm/yr.

The bulk rain gauges associated with the lysimeters collected a total of 738 mm of rainfall beneath the canopy, 5 additional rain gauges collected 601 mm – these values are useful for contrast with the throughfall troughs and the rain gauge in the open

3.6. Canopy Interception

Calculating canopy interception requires a good estimate of rainfall. The tipping bucket rain gauge with the Automatic Weather Station consistently underestimated rainfall when compared with the bulk rain gauge in the clearing, while the throughfall trough in the open collected amounts of rain that were mostly consistent with the bulk gauge. The throughfall trough operated from 3/5/11 to 30/1/12 so provides a good record of daily rainfall for this period. Rainfall data are available from Dunalley (*Bureau of Meteorology*), so rainfall at Dunalley from 1/1/11-3/5/11 was used to help generate an estimate of total rainfall for 2011 of 854 mm.

The throughfall trough under the canopy was plagued with technical problems – either the inlets were blocked by frass or the gauge was unbalanced or misaligned with the siphon. Periods of good data from the throughfall trough were identified by comparison with rainfall measured in the rain gauges beneath the canopy. Sixty-seven days of good throughfall data were collected simultaneously in the open and under the canopy. These days were used to determine the proportion of rainfall that is captured on the foliage on each rainfall day (Figure 8). Approximately 74% of rainfall passed through the canopy to the soil surface and 26% of rainfall was intercepted.

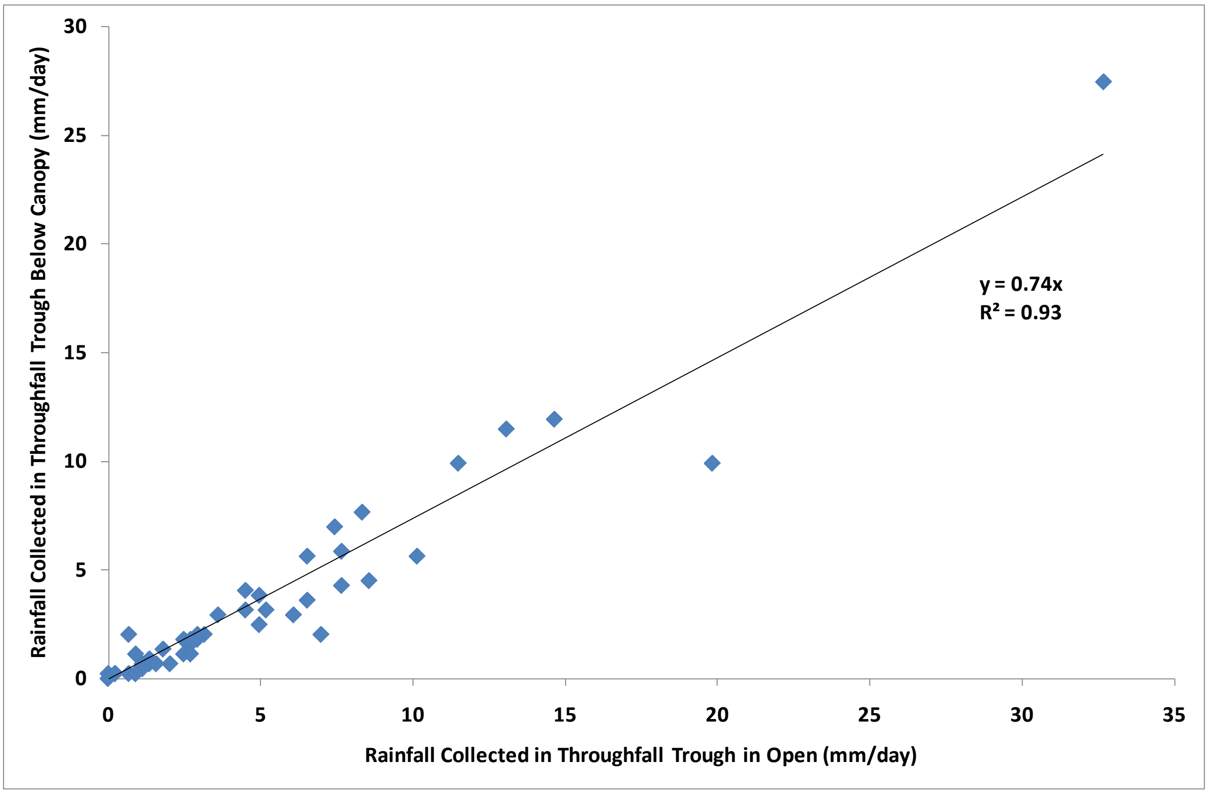

Figure 8. Relationship between rainfall collected in the throughfall troughs in the open and under the canopy at Forestier

Stemflow was measured on 4 trees from 13/4/11 to 12/1/12, a period of 9 months. Stemflow was collected in 20 L containers for three trees, and 1 tree was fitted with a tipping bucket rain gauge. Tree 25 with the tipping bucket rain gauge collected 303.3 L, Tree 32 collected 358.4 L, tree 34 collected 225.5 L and tree 37 collected 324.38 L during the nine months.

To estimate annual stemflow, stemflow needs to be predicted for the first three months of 2011. The relationship between rainfall collected in the open trough and stemflow measured on tree 25 by the tipping bucket rain gauge (Figure 9) was used to estimate stemflow for tree 25 from the rainfall record for 1/1/11 to 12/4/11. Stemflow was estimated at 107.4 L for tree 25 during this period. Stemflow for this period was estimated for the three other trees based on the proportional relationship to tree 25 during the measurement period. This gave total stemflow volumes for 2011 of 409.3, 480.9, 304.5, and 437.4 L for trees 25, 32, 34 and 37 respectively.

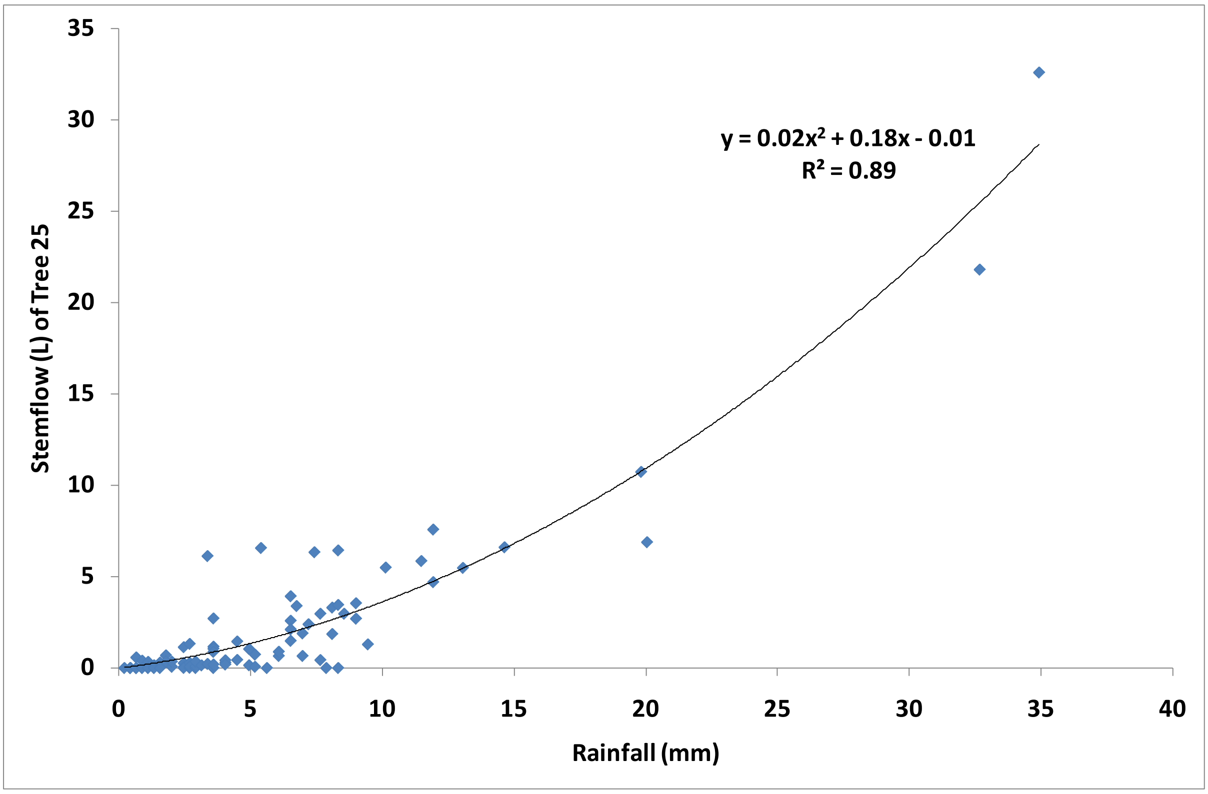

Figure 9. Relationship between daily rainfall and stemflow for tree 25

There was a close relationship (R^2=0.99) between stem diameter and stemflow across the 4 trees (Figure 10). This relationship was used to estimate the stemflow (L) of each tree in the plot, and these values were summed to estimate plot stemflow (16,059 L) then divided by the plot area (400 m^2) to give stemflow of 40.14 mm for the year.

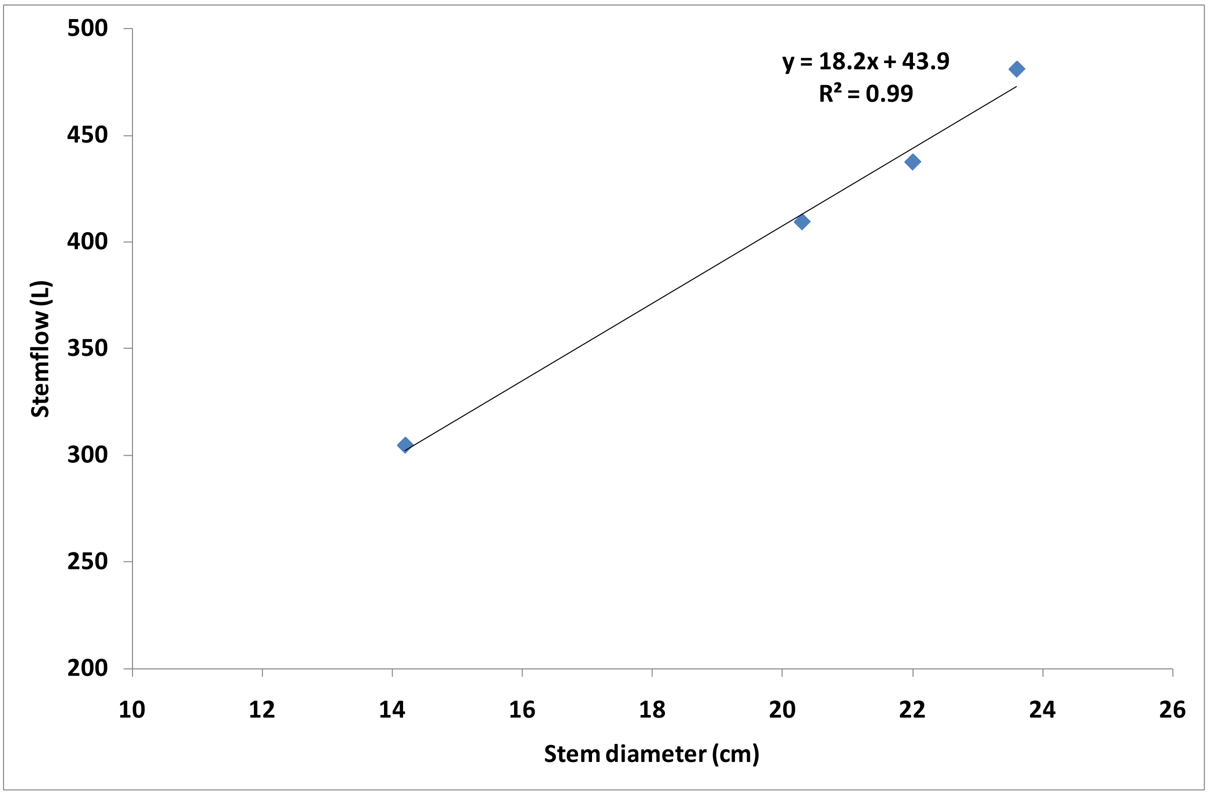

Figure 10. Relationship between stem diameter and stem flow for 4 trees at Forestier

Canopy interception was then calculated to account for 182 mm of the rainfall occurring at the site:

Canopy interception = Rainfall – Throughfall – Stemflow = 854 – 632 – 40 = 182 mm/yr.

3.7. Transpiration

Transpiration is the product of sapwood area and sap velocity. Plot sapwood area, plot sap velocity and plot transpiration were calculated for each day, and transpiration was summed for the period of the study.

Plot sapwood area was estimated for each day by assuming linear growth in sapwood between the sapwood estimates derived from plot inventory.

Sap velocity was measured at 4 locations in each of 4 trees from 24/2/2011 to 7/2/2012. Sensors were allocated to different depths below the cambium to generate sap velocity estimates that were representative of the range of flow rates observed in the sapwood band. Sap velocity was estimated for each day by taking the average value of all operating sensors for that day. There were very few days with no data. Data from 1/11/11 onwards were modified to account for the large step change in sap velocity that occurred when sensors were moved to new positions on this date – it appears that the potting mix that insulates the thermistors in the sensors had degraded and that moving the probes caused the potting mix to fracture leading to the erratic behaviour seen in some probes from this time onwards. Figure 11 shows the daily average sap velocity values after the last months of data were modified.

For the 333 days on which data were collected, sap velocity averaged 6.8 cm/hr. The daily value ranged from 0.29 to 16.43 cm/hr, with a median of 6.47 cm/hr and standard deviation of 3.51 cm/hr.

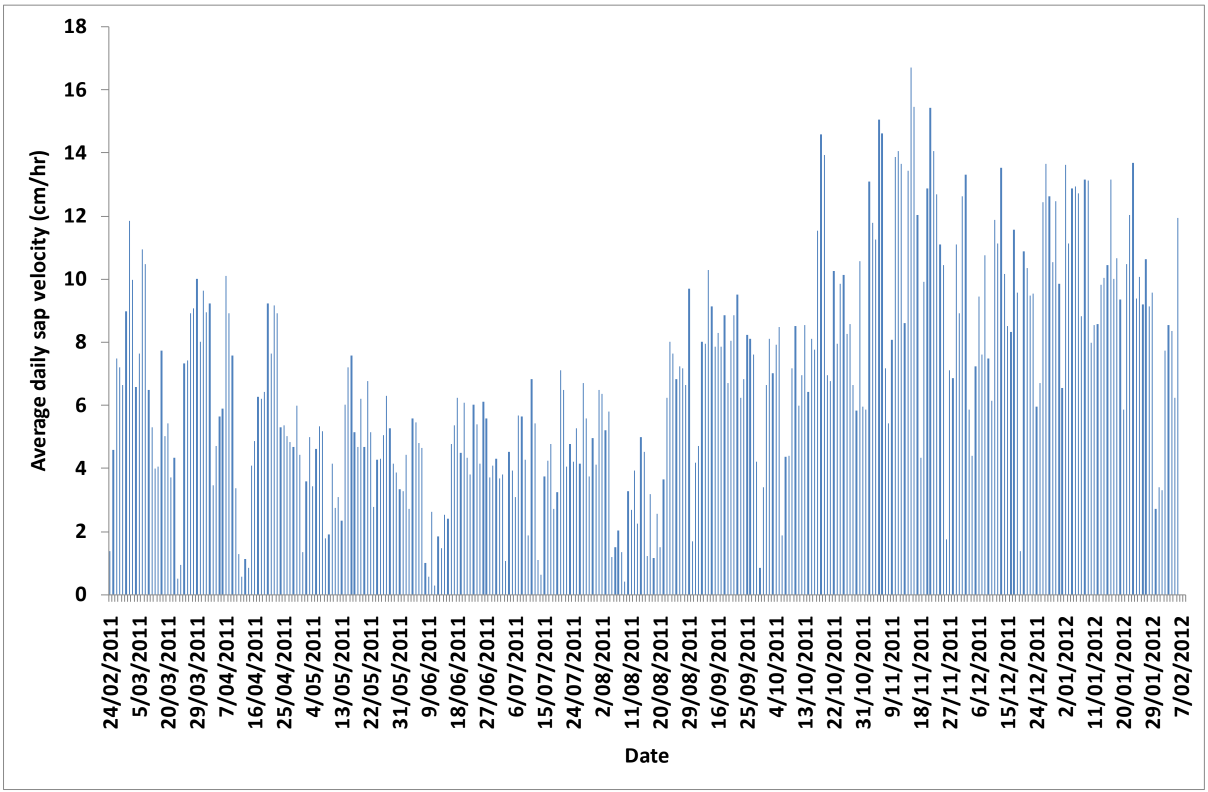

Figure 11. Daily sap velocity averaged across all functioning sensors from the Forestier research site

To provide an estimate of transpiration for a year, transpiration was estimated for 7/2/2011-24/2/2011 by taking the average of January and February data.

Over the period of the study, daily plot transpiration averaged 1.8 mm, with a minimum of 0.2 mm and a maximum of 3.9 mm/day. The sum of transpiration was 558 mm for the year.

3.8. Forestier Water-use Summary

Rainfall for 2011 was estimated at 854 mm. Canopy interception accounted for 182 mm or 21% of the rainfall occurring at the site. Soil evaporation accounted for 52 mm or 6% of the rainfall occurring at the site. Transpiration accounted for 558 mm or 65% of the rainfall occurring at the site. Total water-use was 792 mm for 2011, which is 93% of rainfall.

4. Comparison of Florentine and Forestier Results

Figure 12 is a plot of basal area and sapwood area of individual trees in the Florentine Valley (aged > 5 years or < 5 years), and Forestier. The data were segregated according to age because the ratio of sapwood to basal area changes after the canopy of the plantation closes at around 5 years. The Forestier results fall within the cloud of data points generated in the Florentine Valley, and the lines of best fit overlay each other. Statgraphics "Comparison of regression lines" indicates that there is no significant difference between the two fitted models (α=0.05). This result supports the use of the Florentine sapwood area model in other locations or the inclusion of Forestier data in the Florentine model.

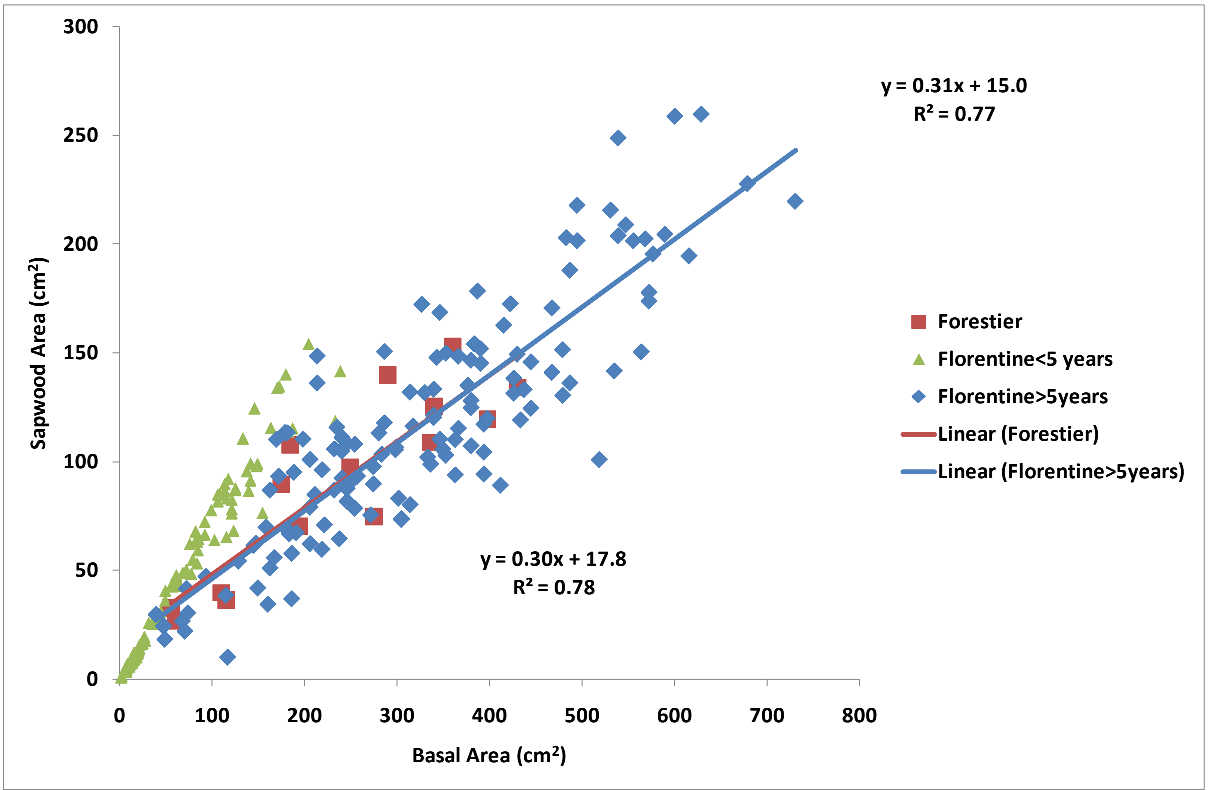

Figure 12. Relationship between basal area and sapwood area for trees aged >5 years at Florentine, aged <5 years at Florentine, and aged 7 at Forestier.

The average sap velocity (cm/hr) at the single Forestier plot was 6.8 cm/hr. The average at Florentine ranged from 5.66 to 8.12 cm/hr across plots when averaged over the entire period of measurement (up to 3 years) (Table 3).

Table 3. Summary statistics for daily sap velocity (cm/hr)

Plot ID	Florentine 22D	Florentine 23C	Florentine 20A	Florentine 21AT	Florentine 21AC	Forestier
Mean sap velocity	6.41	6.54	5.66	8.12	5.92	6.8
Median sap velocity	5.94	6.53	5.04	7.37	5.81	6.47
Minimum sap velocity	1.45	2.24	0.95	2.16	1.83	0.29
Maximum sap velocity	15.05	14.15	14.26	20.11	11.91	16.72
Standard deviation	3.64	3.07	3.27	4.15	2.50	3.51

The sap velocity records for each plot span different periods so represent sap velocity responses to different sets of environmental conditions as well as to different growth stage and management events (e.g. thinning in 21AT). Once the plantations exceed 2 years of age, there is no age related pattern to the mean daily sap velocity of the different plantations (Figure 13, R^2=0.02) with all unthinned plantations exhibiting a mean daily sap velocity between 4 and 7 cm/hr. Thinned plantations exhibit a higher mean daily sap velocity of 7 to 8 cm/hr. The 1 year old plantation exhibited a substantially higher mean daily sap velocity around 10 cm/hr.

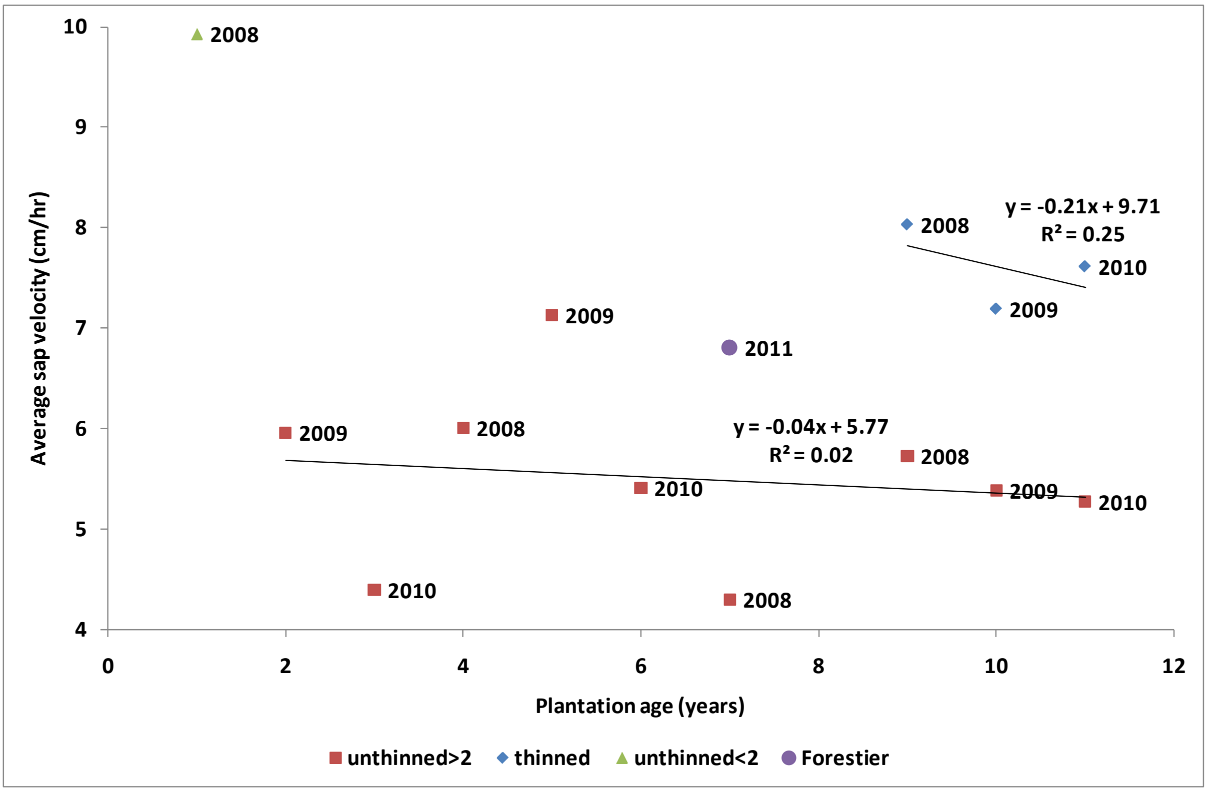

Figure 13. Relationship between plantation age and annual average sap velocity (cm/hr), for Florentine unthinned > 2 years old (red squares), Forestier unthinned < 2 years old (green

triangle), Florentine thinned (blue diamonds) and Forestier (purple circle). Year of measurement is shown for each data point

Sap velocity is highest in the 1 -year-old trees, probably because a small cross-sectional area of stem is supporting a relatively large leaf area when compared with the older trees, and because the low height (short path length) and new wood vessels (higher conductivity) of the seedlings mean that they would have lower hydraulic resistance (Ryan and Yoder, 1997).

4.1. Predicting Forestier water-use with Equation 1

When the basal area (30.18 m^2/ha) and rainfall (854 mm) values for Forestier are entered in Equation 1, the estimated annual water-use is 791 mm. The measured value was 792 mm. This result provides some confidence that Equation 1 derived from Florentine data can be applied to *E. nitens* at Forestier.

5. Process Model Comparisons

Even though the aim of this study was to develop a simple empirical model for water-use prediction, process models such as ProMod (Battaglia and Sands, 1997) and CABALA (Battaglia et al., 2004) can also be used to estimate both the basal area and water-use of plantations in different locations in Tasmania, and thus could possibly be used to test and refine the empirical relationship between these parameters for different regions.

5.1. ProMod

ProMod is a simple model that predicts the growth of forest following canopy closure (Battaglia and Sands, 1997). ProMod also predicts water-use based on a crop factor which is a function of soil water content, and water-use efficiency which is a function of vapour pressure deficit. It requires information about plantation species, location, climate and soil. It tabulates results for growth, summarises information about site conditions and charts growth parameters against plantation age.

ProMod was run for the Florentine and Forestier sites using the Forestry Tasmania Toolbox (Appendix 1). While ProMod gives annual basal area as an output, it does not give as an output annual water-use. Instead, water-use is given as an average annual rate for the plantation when aged greater than 3 years.

Roberts (2011) showed that ProMod basal area estimates were consistent with measurements made in the Florentine Valley. ProMod underestimated basal area for Forestier (20-25 m^2/ha versus 30 m^2/ha), however the measurement plot at Forestier was in the most productive part of the plantation, and ProMod is describing the average condition of a plantation in that region.

Overall, the estimates of basal area from ProMod appear to be representative of the growth occurring at Florentine and Forestier. This is reassuring given that the ProMod growth models are an important component of the FEM. However, the water-use estimates cannot be properly evaluated in their current form.

5.2. CABALA

CABALA is a linked carbon, water and nutrient model designed to be a practical tool to aid forest managers with decision making (Battaglia et al., 2004). CABALA was designed for *Eucalyptus globulus*, but has been partially parameterised for *E. nitens*.

CABALA was run using detailed regimes for each of the five research plots in the Florentine Valley – including accurate planting dates and local daily weather data (Roberts, 2011). Water-use and growth were over-predicted by CABALA. Even with the revised water-use results from the August 2011 report, CABALA continues to overestimate water-use (Figure 15). This is potentially because CABALA is overestimating the basal area of unthinned forests (Figure 14). Benyon et al. (2009) also found that CABALA overestimated water use in the Green Triangle – particularly for non-water-limited plantations. Roberts (2011) reported that CABALA showed promise for estimating *E. nitens* basal area and water-use in the Florentine Valley, but that it does need further calibration. Data from the Florentine study were provided to the creators of CABALA in November 2011 to help facilitate further calibration.

At this stage, therefore, neither CABALA nor ProMod can lend further value to the modelling of *E. nitens* water-use; however they both have the capacity to do so in the future by changing the output format (ProMod) or better calibrating the growth model (CABALA).

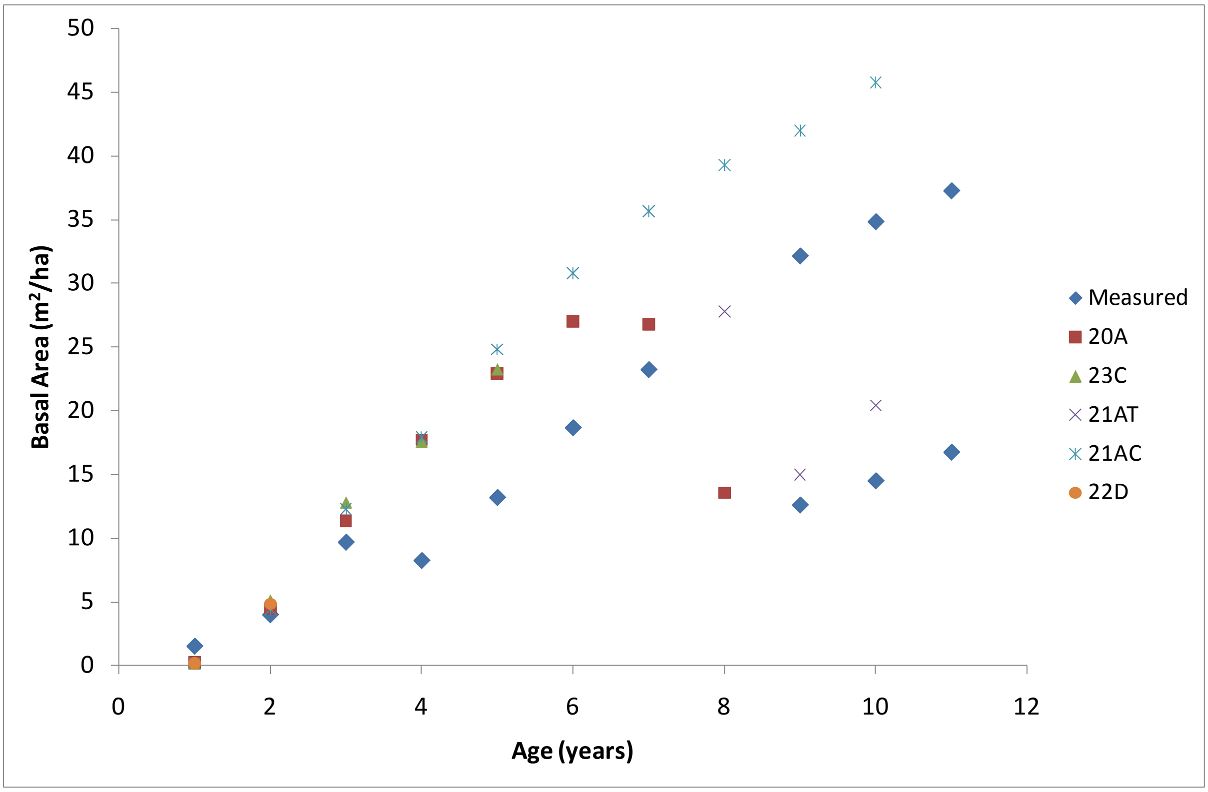

Figure 14. Plantation age and measured basal area (Florentine study, blue diamonds) or predicted basal area for each plot from CABALA.

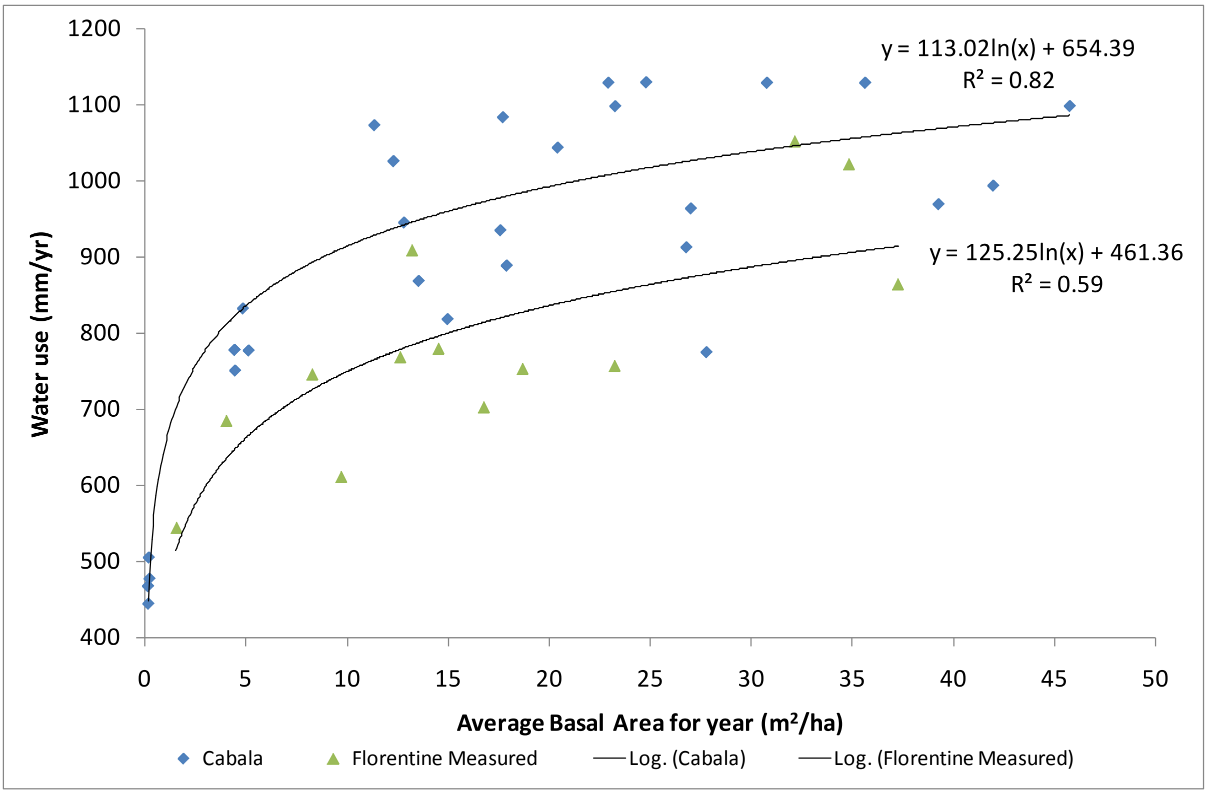

Figure 15. CABALA basal area and water-use predictions (upper line, blue diamonds) compared with Florentine measurements (lower line, green triangles).

6. Final water-use function

The recommended function for inclusion in the FEM to estimate *E. nitens* water-use in Tasmania is:

$$WU = 149+11.0*BA+0.361*R \qquad \text{Equation 1.}$$

Where WU is water-use in mm/yr, BA is plot basal area in m^2/ha, and R is rainfall in mm/yr.

This function is better than the Roberts (2011A) function (Figure 4.) because it allows water-use to be varied in response to differences in annual rainfall.

Maps of rainfall isohyets are available for Tasmania. Grids and shape files for rainfall can be downloaded from http://www.bom.gov.au/jsp/ncc/climate_averages/rainfall/index.jsp and could potentially be included in the FEM, or, if more detailed rainfall data are desired, actual data or synthetic rainfall data from Silo Data drill for specific sites could be included in the FEM.

Inclusion of potential evaporation maps to set the upper limit for water-use would prevent estimates of water-use being made that exceed what is physically possible. Grids and shape files for potential evaporation can be downloaded from http://www.bom.gov.au/jsp/ncc/climate_averages/evaporation/index.jsp .

7. Modelling water-use of plantations using Forestry Tasmania's Forest Estate Model

The purpose of collecting water-use data was to construct a simple empirical water-use model that could be included in FT's Forest Estate Model (FEM).

Forest Estate Models are used by forest companies to estimate volumes of standing and harvested timber through time and to predict and compare financial returns. They enable managers to schedule their activities based on constraints such as the need to operate on the basis of sustainable yield, and aid decision-making by allowing the effects of different management scenarios on wood production and income to be compared.

Forestry Tasmania uses Woodstock (Remsoft Spatial Planning System) FEM. Woodstock dynamically models the growth of forests and plantations using yield tables.

The FEM performs calculations for each defined planning unit, which is usually a coupe, but can provide analyses for a plot of land, property, compartment, cluster of coupes, catchment or the whole forest estate by combining results from multiple planning units. Inventory data, growth models, information about species, age, stocking, management regimes, site quality and the location and extent of each planning unit, along with constraints or production objectives, are used by the FEM to generate estimates of basal area for the planning unit (Figure 16). These in turn are converted to estimates of the volume of timber harvested and the volume standing. Financial information can be included to produce estimates of the value of sales and the standing timber.

If Equation 1 can be included in the FEM, then water-use and wood production can be assessed simultaneously.

Equation 1 was included in the FEM. For this study, a minimum water-use of 591 mm/yr was set (this represents minimum water-use from a site with no trees), and a maximum water-use of 915 mm/yr was set (this represents mean annual PET for the Florentine Valley). Average rainfall for the Florentine Valley of 1222 mm/yr was used.

To demonstrate how inclusion of Equation 1 in the FEM will work, predictions were made of wood volumes, basal area and water-use over a 90-year period for all of the *E. nitens* plantations occurring within the Florentine Valley (Figure 17). These plantations ranged in age from 0-19 years at the start of the assessment, and covered a total area of 1532 ha. Predictions were also made for a single coupe.

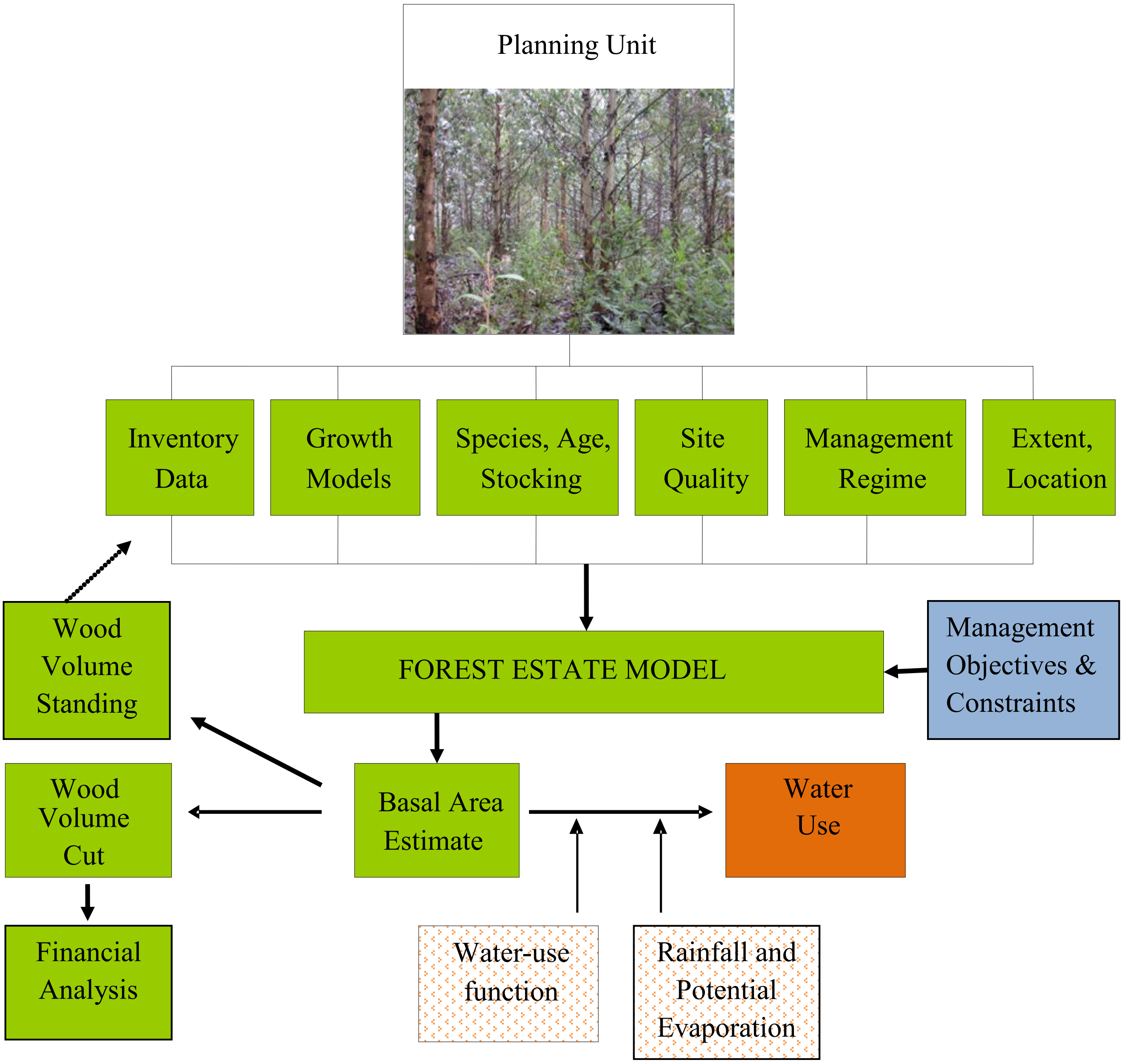

Figure 16. Schematic diagram of FEM structure, where green segments indicate existing components, blue represents management objectives and constraints that can be changed in accordance with company policy decisions, orange and the orange white segments indicate processes that are being incorporated as a result of this study.

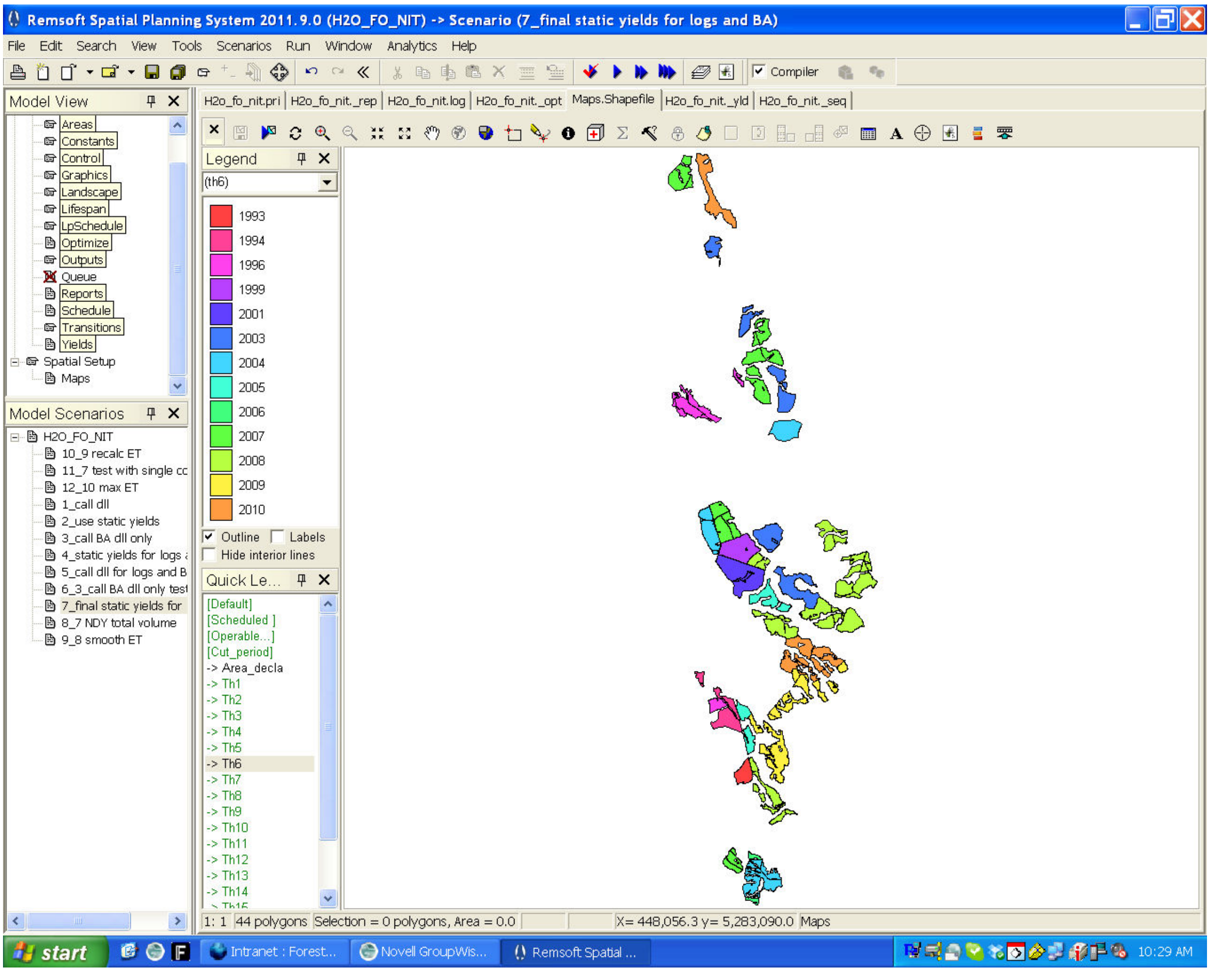

Figure 17. Screen shot showing plantations in the FEM Florentine Valley assessment, colour-coded by year of planting

The FEM ran three scenarios: a scenario where NPV of the plantations is maximised (Figure 18), a scenario where the plantations are managed to smooth water-use (Figure 19), and a scenario to smooth wood supply (Figure 20). An example of the output for a single coupe is also provided (Figure 21). For each scenario, screenshots of charts taken directly from the FEM are provided. The first chart in each screenshot shows the volume of wood harvested each year, the second shows the basal area of the standing trees, and the third shows the water-use of the plantations. The charts in Figures 18, 19 and 20 represent the wood volume, basal area and water-use of the total 1532 ha. To get wood volume in m^3/ha, and basal area in m^2/ha, the values on the vertical axes of the charts need to be divided by the total number of hectares (1532). Water-use is given as an average annual value across the whole area. Annual statistics for wood volume, basal area and water-use of the plantations are readily obtained from the FEM in tabular form to aid in further analysis and decision making if required.

The charts demonstrate that managing plantations to produce smooth water-use and smooth wood production is compatible (see similarity between Figure 19 and Figure 20) – managing for one produces the other. This lends further support to the concept of a regulated forest minimising changes to hydrological systems (Hennes et al., 1971).

In addition to producing the charts and basal area, wood volume and water-use predictions, the FEM produces a schedule that shows how management objectives can best be met. The FEM indicates when and where activities such as planting, thinning and harvesting should occur. FEM output is readily transferred to Microsoft Access where specific queries can be made to generate management plans over whatever term is deemed practical (Table 4).

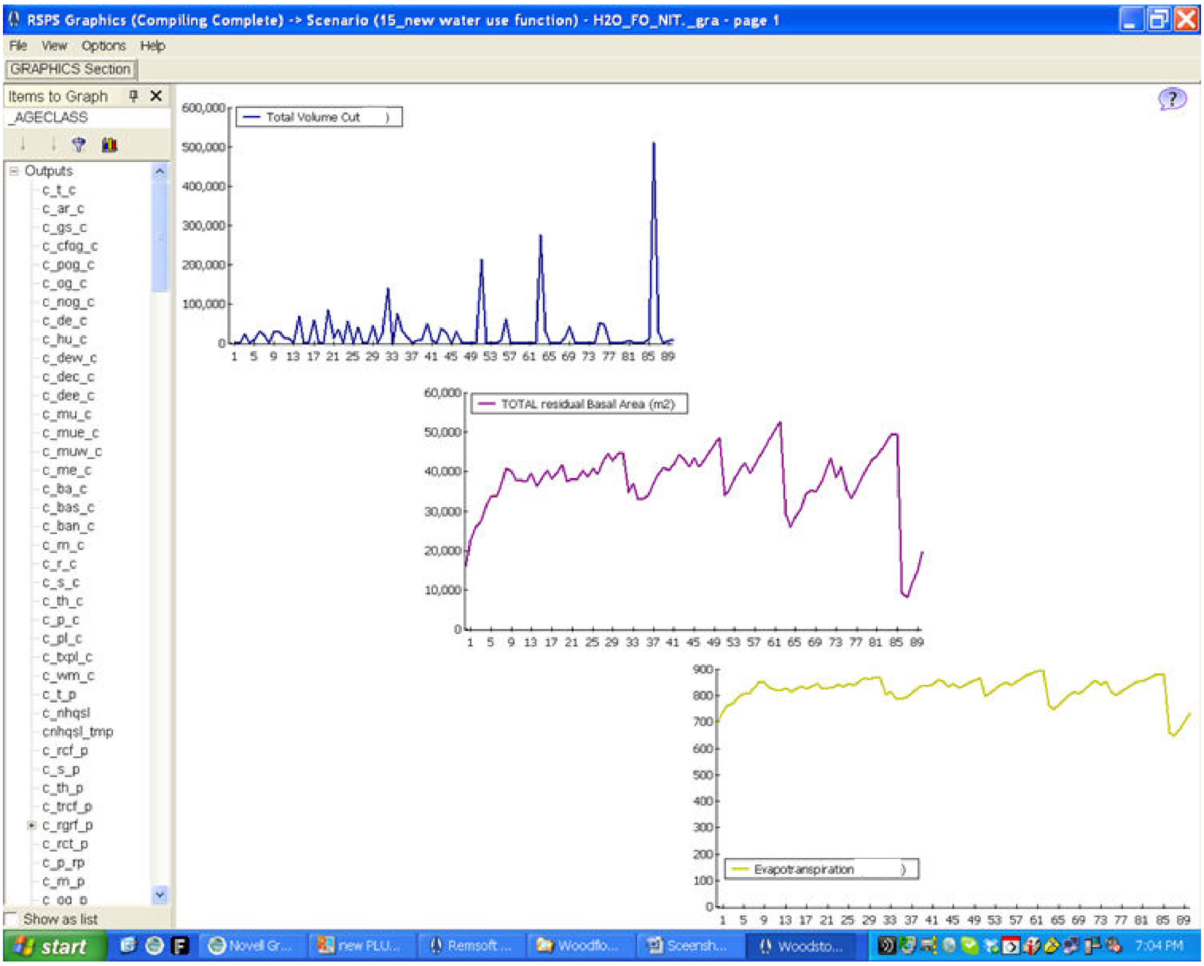

Figure 18. FEM screenshot showing volume cut (m^3/yr), standing basal area (m^2) and evapotranspiration (mm/yr) for each year of a 90-year simulation where objective is to maximise net present value for 1532 ha of *E. nitens* plantation in the Florentine Valley

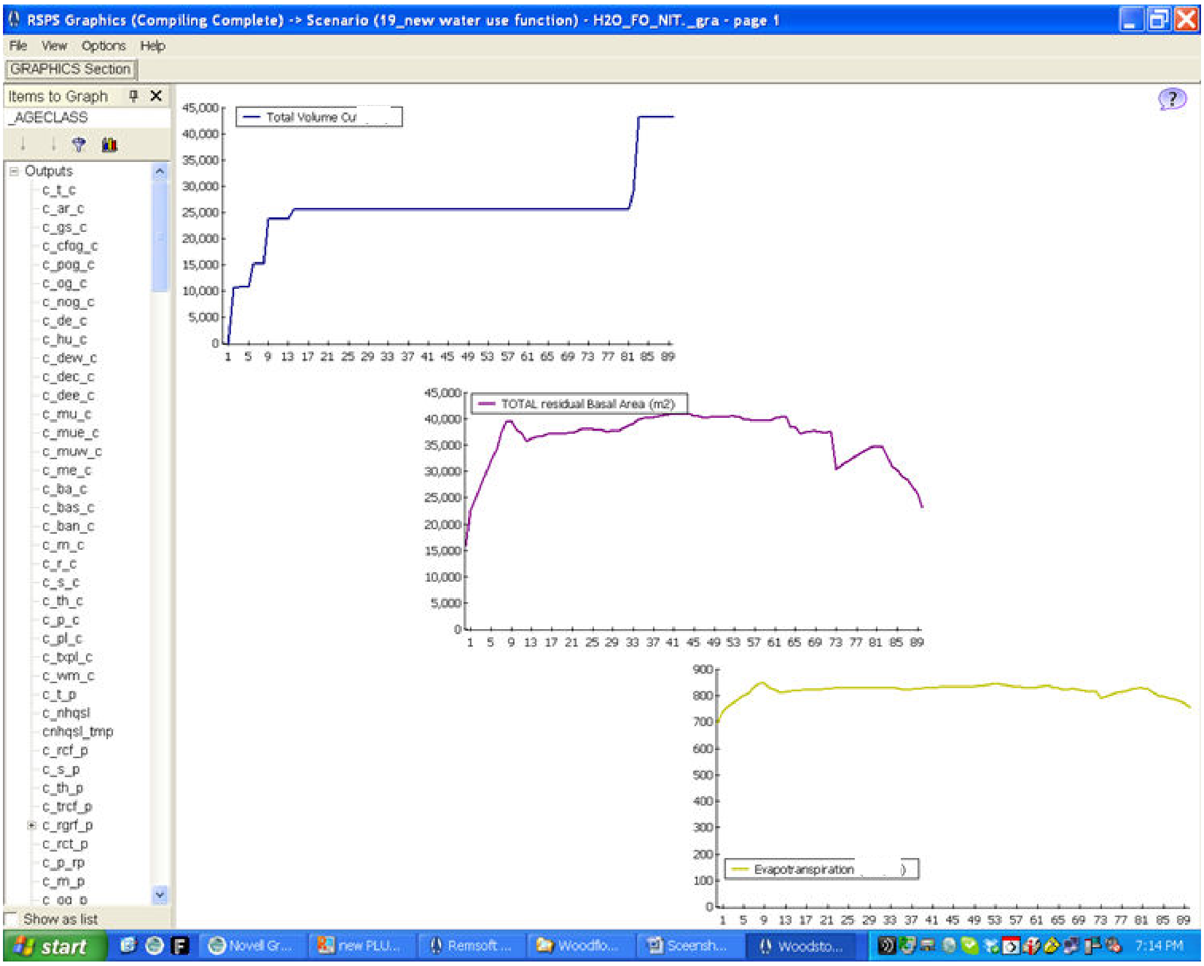

Figure 19. FEM screenshot showing volume cut (m^3/yr), standing basal area (m^2) and evapotranspiration (mm/yr) for each year of a 90-year simulation where objective is to have non-declining total volume cut and smoothed evapotranspiration (+/- 10%) scenario for 1532 ha of *E. nitens* plantation in the Florentine Valley

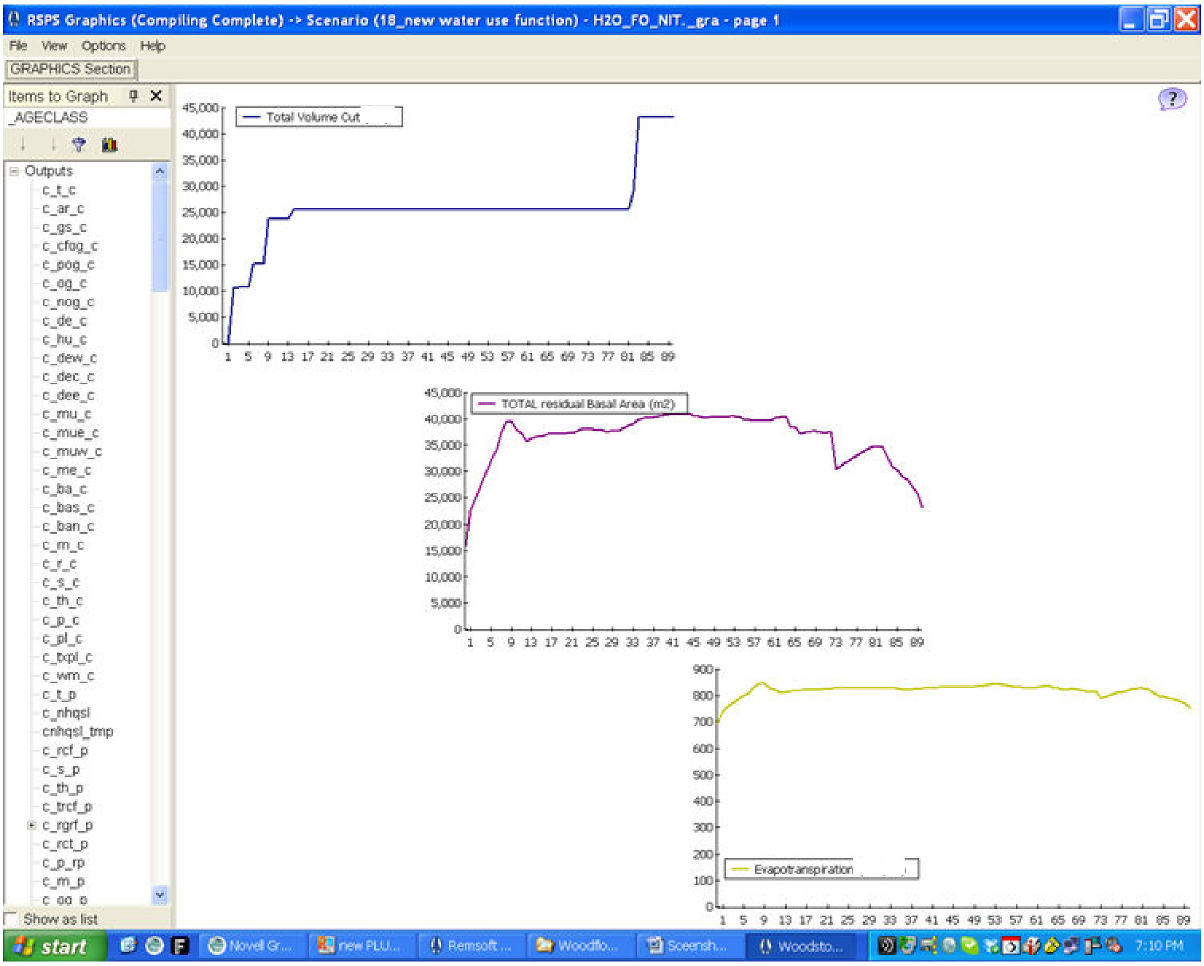

Figure 20. FEM screenshot showing volume cut (m^3/yr), standing basal area (m^2) and evapotranspiration (mm/yr) for each year of a 90-year simulation where objective is to maximise Net Present Value with non-declining total volume cut for 1532 ha of *E. nitens* plantation in the Florentine Valley

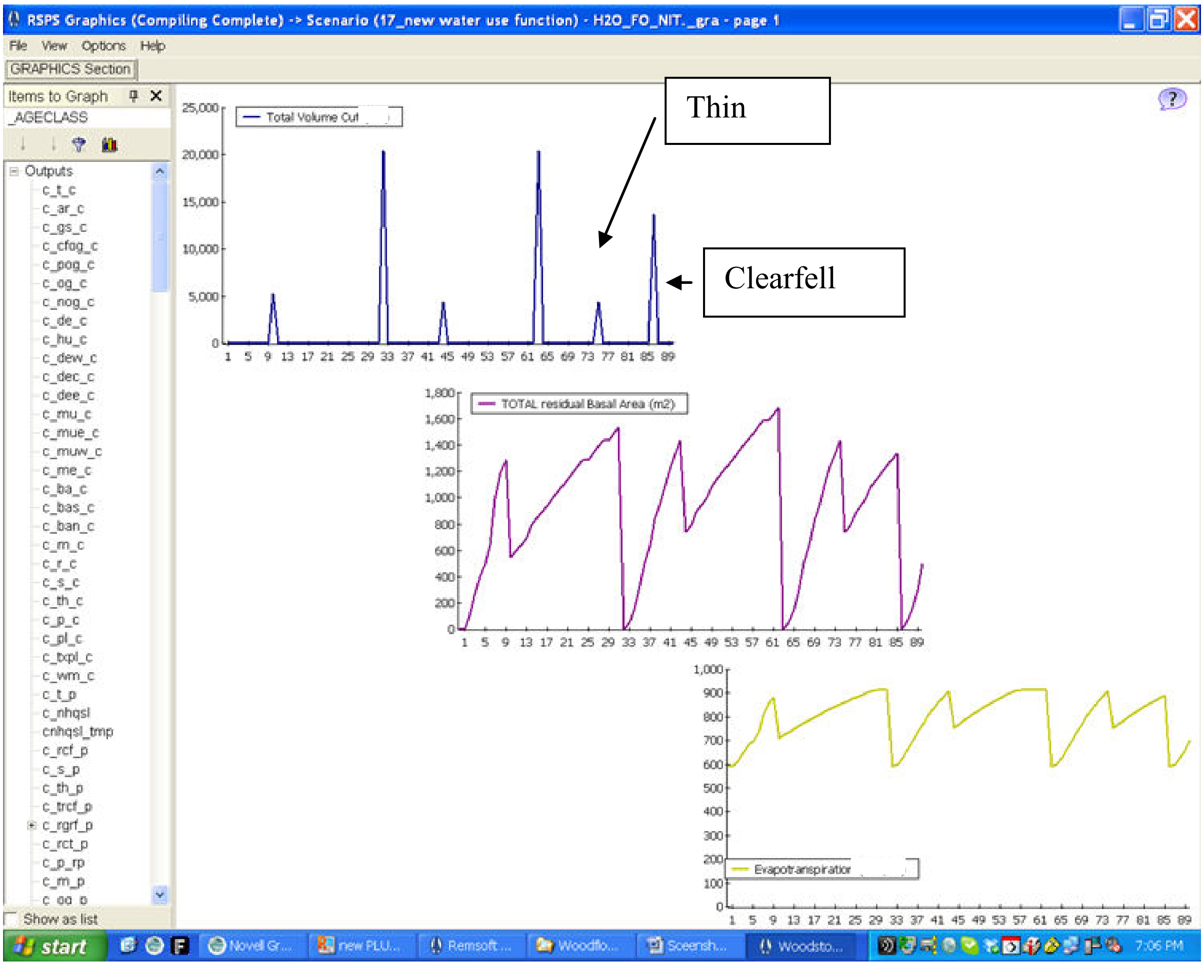

Figure 21. FEM screenshot for an individual *E. nitens* plantation showing volume cut (m^3/yr), basal area (m^2) and evapotranspiration (mm/yr) over 90 years (three rotations)

Table 4. Schedule of activities that will maximise Net Present Value with non-declining total volume cut and smoothed water-use (+/- 10%). First 15 years of a 90-year scenario shown.

Coupe ID	Year	Scheduled Activity	Number of Hectares
FO020A	2	Thin	44
FO020A	3	Thin	39
FO015B	4	Thin	23
FO015D	4	Thin	4
FO020G	4	Thin	36
FO034F	4	Thin	7
FO015D	5	Thin	38
FO023C	5	Thin	12
FO015B	6	Thin	17
FO034F	6	Thin	56
FO030A	7	Thin	30
FO032X	7	Clearfell	17
FO006E	8	Thin	17
FO014D	8	Thin	35
FO032X	8	Clearfell	7
FO034F	8	Thin	9
FO006E	9	Thin	25
FO014G	9	Thin	37
FO019C	9	Thin	2
FO022I	9	Thin	32
FO027D	9	Thin	16
FO030G	9	Thin	31
FO033B	9	Thin	21
FO018C	10	Thin	74
FO019C	10	Thin	33
FO020F	10	Thin	50
FO021D	10	Thin	17
FO026A	10	Thin	47
FO027D	10	Thin	16
FO030G	10	Thin	16
FO013W	11	Clearfell	17
FO014Y	11	Clearfell	1
FO028B	11	Thin	67
FO030V	11	Thin	74
FO006C	12	Thin	59
FO013W	12	Clearfell	23
FO026Z	12	Thin	98
FO013W	13	Clearfell	5
FO021A	13	Clearfell	29
FO020A	14	Clearfell	14
FO021A	14	Clearfell	22
FO020A	15	Clearfell	33
FO021A	15	Clearfell	5

8. Future research needs

The data collected at Florentine and Forestier support the use of a single water-use model which includes a rainfall term for *E. nitens* in these locations. Without studies in a sample of other locations experiencing vastly different climate and rainfall, or the use of calibrated models for other locations, conclusions cannot yet be made about the general applicability of the model to plantations in areas experiencing vastly different conditions.

E. nitens was selected for this study because it is a widely planted species, for which little water-use data have been collected, and was thus deemed to be a good species for a pilot study. The sites measured had *E. nitens* growing in uniform stands with sparse understorey which reduced the complexity of measurement. The methods used in *E. nitens* to measure and model water-use are likely to be successful for other tree-dominated ecosystems including plantations and native forests, although it is possible that further parameters such as age, understorey density, soil water-holding capacity, or access to groundwater (Benyon et al., 2009) may need to be added to the model to make it more widely applicable. Existing data on streamflow and water-use for other vegetation types may allow basal area: water-use models to be constructed for them, or new studies or calibration of process models may be required.

Being able to predict the water-use of an array of commercial forest and plantation types will enable their influence on water resources to be evaluated. This is useful for forest managers who are exchanging trees for trees, but less useful for forest managers that are converting other vegetation types such as grassland to plantation, and less useful for catchment managers who may want to know the influence of all land management activities occurring in a catchment. Being able to quantify the water-use of all land use types for inclusion in the FEM would allow an even more useful tool to be developed.

The data collected in the Florentine and Forestier studies have only been studied at the annual level. The data can potentially be used for a range of other purposes such as comparison to streamflow studies, physiological studies, linkage to leaf area measurements made by University of Tasmania, and comparison to LIDAR data as collected at Florentine during the study period for validation of estimates of plantation parameters made from LIDAR. Daily, monthly and seasonal values can be compared to climate to better understand the influence of climatic variables on plantation water-use. The associations between plantation water-use, streamflow, and groundwater need further exploration.

Uncertainties have not been calculated for any of the water-use measurements. Identifying and quantifying all of the potential sources of error in the water-use measurements would help to define the certainty of the results.

Any FEM water-use model is only as good as the basal area estimates that it is based upon. ProMod is the model that underpins FT's FEM. ProMod predicted basal area to within 10% of the measured value in the Florentine Valley. ProMod underestimated basal area at the single Forestier site of age 6 -7 years (20-25 m^2/ha predicted versus a value of around 30 m^2/ha measured at the site), however the research plot is located in a better part of the stand so it is probable that ProMod represents the average basal area of the stand rather than the basal area of the best quality part of the stand. Growth models should continue to be developed and refined as new data are collected.

9. Discussion and Conclusions

Annual plantation water-use was strongly linked to plantation basal area. It is not common for researchers to compare plot water-use to plot basal area, although they frequently identify strong relationships between stem diameter and stem transpiration (Vertessy et al., 1995; Moore, 1993; O'Grady et al., 1999; Kalma et al., 1997). It is also possible for there to be no identifiable relationship between stem diameter and stem transpiration (Forrester et al., 2010). Basal area is a function of stem diameter, so where relationships are found between transpiration and stem diameter, they will also exist with basal area.

There was a strong relationship between sapwood area and stem diameter (or basal area calculated from stem diameter) in *E. nitens* and this was consistent between sites. It is typical for these parameters to be strongly linked (Roberts, 2001; Macfarlane et al., 2010; Benyon and Doody, 2004; Forrester et al., 2010).

Rainfall in the year of measurement also influenced water-use in the Florentine Valley. Wet rough surfaces such as forests will , in general, have actual evapotranspiration rates at the potential rate until the water supply for the soil becomes limiting (Beven, 2005). The amount and seasonal distribution of rainfall will therefore affect annual water-use.

For the plantation ages measured, basal area appears to provide an adequate description of site quality to predict water-use. Basal area reflects the influence of the suite of biotic and abiotic influences on growth and water-use for the lifetime of the plantation. Leaf area (which may be available for the plantation estate in the future after collection and processing of LIDaR) may also be useful for determining water-use of plantations in the future. Leaf area was an important determinant of plantation water-use (or transpiration) at other locations (Hatton and Wu, 1995; Forrester et al., 2010). Leaf area will be the subject of further study.

ProMod and CABALA were the process models that are most likely to be able to predict basal area and water-use of *E. nitens* in Tasmania. ProMod needs to be modified to give annual water-use estimates. CABALA needs further calibration for *E. nitens*. These models, when correctly calibrated will potentially be useful for refining the basal area: water-use model and expanding it to other regions.

The data collected so far do not indicate a need to use separate basal area: water-use functions for *E. nitens* in different parts of Tasmania. However it would be wise to conduct further testing to show that this is true. Use of the model on mainland Australia or in regions experiencing substantially different conditions would require testing to determine the effects of different productivity, rainfall, soil types and PET.

Predicting plantation water-use from forest estate models makes sense for a number of reasons:

- Most sizeable forest companies already have FEMs. They are vital tools for forest management planning.

- FEMs represent the best available source of information about the plantation and forest estate, including species, structure, management and growth. The quality of this information is improving all the time as new data are incorporated.
- FEMs are optimisation tools that allow a range of scenarios to be assessed given a host of constraints and they are able to compare the financial outcomes, wood production, product mix and standing volumes that will result from various scenarios.
- FEMs can schedule events over long periods to best allow management objectives to be achieved.

A simple empirical model links *E. nitens* plantation water-use to plantation basal area. Most Australian attempts to quantify the effects of plantations on water resources have focussed on streamflow rather than water-use and none have attempted to link with existing forest management tools. Forest companies do not manage entire catchments, do not know where all streams are or how much water is draining from them and do not have the tools or capacity to operate catchment models for anything other than small-scale studies. This makes streamflow an impractical basis for planning forest management to benefit water resources.

The National Water Initiative recognises that large-scale plantation forestry may intercept significant volumes of water, and makes provision for the regulation of large-scale plantation forestry to reduce the risk to water access entitlements or to achieve environmental objectives. Forest industry, land managers and regulators are not currently in a position to quantify large-scale plantation interception in a way that takes account of the variation that occurs in interception in response to plantation health and growth. Incorporation of water-use data in FEMs could produce water interception predictions for plantations to inform these decisions.

10. Recommendations

Based on the results of this study, we recommend that:

- Spatial rainfall data are included in Forestry Tasmania's FEM so that the water-use function can be easily applied to all *E.nitens* plantations in Tasmania.
- Existing water-use and streamflow data for other plantation species and native forests are reviewed to see if basal area: water-use functions can be created for them with minimal collection of new data.
- The outputs from ProMod are tweaked so that annual water-use estimates are provided for comparison to measured values.
- CABALA is calibrated for *E.nitens* using data collected during this study.
- Plantation owners that need or choose to consider plantation water-use during their planning processes consider including water-use functions in their forest estate models to aid in decision making.
- Further data collection, use of process models and creation of empirical models is undertaken to enable the development of water-use functions for a wider range of plantation species.
- When appropriate, regulators consider evaluating the impacts of proposed management on water resources from a water-use rather than streamflow perspective.

11. References

Battaglia, M., and Sand, P. 1997. Modelling Site Productivity of *Eucalyptus globulus* in Response to Climatic and Site Factors. Australian Journal Plant Physiology 24:831-850.

Battaglia, M., Sands, P., White, D., and Mummery, D. 2004. CABALA: a linked carbon, water and nitrogen model of forest growth for silvicultural decision support. Forest Ecology and Management 193 (1-2): 251-282.

Benyon, R.G. and Doody, T.M. 2004. Water use by tree plantations in south east South Australia. CSIRO Forestry and Forest Products Technical Report No. 148.

Benyon, R.G., Doody, T.M., Theiveyanathan, S. and Koul, V. 2009. Plantation forest water use in southwest Victoria. Forests and Wood Products of Australia, Sustainability and Resources, Project No: PNC064-0607, June 2009.

Best, A., Zhang, L., McMahon, T., Western, A., and Vertessy, R. 2003. A critical review of paired catchment studies with reference to seasonal flows and climatic variability. CSIRO Land and Water Technical Report No. 25/03.

Beven, K. 2005. Rainfall-runoff modelling. John Wiley and Sons, England.

Bosch, J.M., and Hewlett, J.D. 1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapotranspiration. Journal of Hydrology 55: 3-23.

Bren, L., and Hopmans, P. 2007. Paired catchments observations on the water yield of mature eucalypt and immature radiata pine plantations in Victoria, Australia. Journal of Hydrology 336: 416-429.

Bren, L., Lane, P., and McGuire, D. 2006. An empirical, comparative model of changes in annual water yield associated with pine plantations in southern Australia. Australian Forestry 69 (4): 275-284.

Brown, A.E., Hairsine, P.B. and Freebairn, A. 2006. The development of the Tasmanian Land Use Change and Streamflow (TasLUCaS) tool. Report to the Tasmanian Natural Resource Management Committees. CSIRO Land and Water Science Report No. 54/06, July 2006.

Cornish, P., and Vertessy, R. 2001. Forest age induced changes in evapotranspiration and water yield in eucalypt forest. Journal of Hydrology 150: 301-322.

Council of Australian Governments (COAG) 2005, Intergovernmental Agreement on a National Water Initiative, between the Commonwealth of Australia and the Governments of New South Wales, Victoria, Queensland, South Australia, the Australian Capital Territory, the Northern Territory, Tasmania and Western Australia.
(http://www.nwc.gov.au/reform/nwi)

Department of Sustainability and Environment. 2011. Managing adverse water resource impacts of land use changes. Policy Paper, State Government of Victoria, November 2011.

Department for Water. 2012. Lower Limestone Coast Water Allocation Plan Policy Principles. Lower Limecoast Water Allocation Plan Taskforce. South Australia.

Feikema, P., Beverly, C., Morris, J., Collopy, J., Baker, T. and Lane, P. 2007. Predicting the Impacts of Plantations on Catchment Water Balances Using the 3PG Forest Growth Model. In Oxley, L. and Kulasiri, D. (eds) MODSIM 2007 International Congress on Modelling and Simulation. Modelling and Simulation Society of Australia and New Zealand, December 2007, pp. 2237-2243.

Forest Practices Board. 2000. Forest Practices Code, Forest Practices Board, Hobart, Tasmania.

Forest Practices Tribunal. 2009. The hearing of an appeal against the decision of the Forest Practice Authority to grant an application for declaration of land at Irishtown near St Marys, as a Private Timber Reserve. DW Clement on behalf of TB O'Neill v Forest Practices Authority and RB Curran. 16 March 2009.

Forrester, D.I., Collopy, J.J. and Morris, J.D. 2010. Transpiration along an age series of *Eucalyptus globulus plantations* in southeastern Australia. Forest Ecology and Management 259: 1754-1760.

Grant, J., Laffan, M., Hill, R., and Nielson, W. 1995. Forest soils of Tasmania. A handbook for identification and management. Forestry Tasmania, Hobart.

Harvey, D. 2009. Accounting for plantation forest groundwater impacts in the lower South East of South Australia. Science, Monitoring and Information Division, Department of Water, Land and Biodiversity Conservation 2009/13.

Hatton, T. and Vertessy, R. 1990. Transpiration of plantation *Pinus radiata* estimated by the heat pulse method and the bowen ratio. Hydrological Processes 4: 289-298.

Hatton, T. and Wu, H.I. 1995. Scaling theory to extrapolate individual tree water use to stand. Hydrological Processes 9: 5-6.

Hennes, L.C., Irving, M.J., and Navon, D.I. 1970. Forest Control and Regulation: a comparison of traditional methods and alternatives. USDA Forest Service Research Note PSW-237.

Hydro Tasmania Consulting. 2007. Water Availability and Forest Landuse Planning Tool Report. Hydro-Electric Corporation, September 2007.

Kalma, S., Thorburn, P. and Dunn, G. 1997. Using heat pulse and deuterium tracing techniques to estimate tree water use. In Subsurface Hydrological Responses to Land Cover and Land Use Changes, ed. M. Taniguchi, Kluwer Academic Publishers, Boston, pp. 47-60.

Macfarlane, C., Bond, C., White, D.A., Grigg, A.H., Ogden, G.N. and Silberstein, R. 2010. Transpiration and hydraulic traits of old and regrowth eucalypt forest in southwestern Australia. Forest Ecology and Management 260: 96-105.

McJannet, D., Vertessy, R. and Clifton, C. 2000. Observations of evapotranspiration in a break of slope plantation susceptible to periodic drought stress. Tree Physiology 20: 169-177.

McLarin, M., Osborn, T., and Bennett, L. 2006. Creating dynamic yield tables for forest estate modelling. Australian Forestry 69(2):79-82.

Moore, S. 1993. Estimating stand transpiration in a *Eucalyptus populnea* woodland. In School of Resource and Environmental Management, Australian National University, Canberra, pp. 97.

O'Grady, A., Eamus, D. and Hutley, L. 1999. Transpiration increase during the dry season: patterns of tree water use in eucalypt open forests of northern Australia. Tree Physiology 19: 591-597.

Putuhena, W. and Cordery, I.: 1996, Estimation of interception capacity of the forest floor, Journal of Hydrology 180: 283–299.

Rayner, D. 2006. Australian synthetic dailuy Class A pan evaporation. Queensland Department of Natural Resources and Mines Technical Report, December 2005. (http://www.longpaddock.qld.gov.au/silo/documentation/AustralianSyntheticDailyClassAPanEvaporation.pdf)

Roberts, S.L. 2001. Water yield and transpiration of *Eucalyptus sieberi* forests of different age. PhD Thesis, Department of Civil and Environmental Engineering, The University of Melbourne.

Roberts, S., Montagu, K., Walsh, P., Barton, C., Cowie, A., and Parekh, J. 2002. Reintroducing trees to dryland salinity prone regions of New South Wales. Proceedings of the National Low Rainfall Farm Forestry Conference, Horsham, pp. 169-180.

Roberts, S. 2010. Water-use of *Eucalyptus nitens* plantations in the Florentine Valley, Tasmania - Preliminary Results. Report submitted to FWPA, August 2010. Plantations Branch, Division of Forest Research and Development, Forestry Tasmania.

Roberts, S. 2011. Predicting *Eucalyptus nitens* Plantation water-use using growth parameters – comparisons of field results with existing models. Report submitted to FWPA April 2011. Plantations Branch, Division of Forest Research and Development, Forestry Tasmania.

Roberts, S. 2011A. Water-use of *Eucalyptus nitens* plantations in the Florentine Valley, Tasmania. Report submitted to FWPA, August 2011. Plantations Branch, Division of Forest Research and Development, Forestry Tasmania.

Roberts, S., and Barton-Johnson, R. 2009. Prediction of *Eucalyptus nitens* plantation water-use with tree growth parameters: Plantation water-use research, Florentine Valley, Tasmania - Site Establishment Report. Report submitted to FWPA, December 2009. Plantations Branch, Division of Forest Research and Development, Forestry Tasmania.

Roberts, S., Vertessy, R. and Grayson, R. 2001. Transpiration from *Eucalyptus sieberi* forests of different age. Forest Ecology and Management 143: 153-161.

Ryan, M. and Yoder, B. 1997. Hydraulic limits to tree height and growth: What keeps trees from growing beyond a certain height? Bioscience 47(4): 235-242

Sands, P., Battaglia, M. and Mummery, D. 2000. Application of process-based models to forest management: experience with PROMOD, a simple plantation productivity model. Tree Physiology 20 (5-6):383-392.

Silo Data Drill. Queensland Department of Environment and Resource Management. (http://www.derm.qld.gov.au/services_resources/item_details.php?item_id=33897)

Vertessy, R., Benyon, R., O'Sullivan, S. and Gribben, P. 1995. Relationships between stem diameter, sapwood area, leaf area and transpiration in young mountain ash forest. Tree Physiology 15: 559-567.

Vertessy, R.A. 2001. Impacts of plantation forestry on catchment runoff. In: E.K. Nambiar and A.G.Brown (Eds.) Plantations, Farm Forestry and Water, Proceedings of a National Workshop, Melbourne, July 21-22, 2000. RIRDC Report No. 01/20.

Vertessy, R., Watson, F. and O'Sullivan, S. 2001. Factors determining relationships between stand age and catchment water balance in mountain ash forests. Forest Ecology and Management 143: 13-26.

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13. Appendix

ProMod outputs for Florentine and Forestier

13.1 ProMod outputs for Florentine

Site productivity **FFT v4.158** Saved 29/3/2011

FlorentineHydrologyStudy ***E. nitens***

Location: Easting = 456323 Northing = 5282925 Aspect = W Elevation (m) = 400

Soil:
Slope % = 1 Depth (cm) = 200 Stoniness % = 20
Fertility: not limited Texture: well-structured clay-loam Drainage: good drainage

Climate:

Month	Temp(max) (°C)	Temp(min) (°C)	Rainfall (mm)	Radiation ($MJ/m^2/day$)	Pan Evap. (mm)	Rain Days
Jan	21.0	8.0	82	22.0	4.0	18.0
Feb	21.0	8.0	66	19.0	4.0	16.0
Mar	18.0	7.0	85	15.0	3.0	19.0
April	15.0	5.0	111	10.0	2.0	23.0
May	12.0	4.0	134	7.0	1.0	26.0
June	10.0	2.0	124	6.0	1.0	25.0
July	9.0	1.0	147	6.0	1.0	27.0
Aug	10.0	2.0	155	9.0	1.0	27.0
Sep	12.0	3.0	159	12.0	2.0	25.0
Oct	15.0	4.0	145	17.0	3.0	24.0
Nov	17.0	6.0	116	20.0	3.0	21.0
Dec	19.0	7.0	110	21.0	4.0	20.0

Site:

SQ index (ProMod) = 30.0 m

Mean maximum temp. = 14.9 °C
Mean minimum temp. = 4.8 °C
Mean daily temp. = 9.8 °C
Total solar radiation = 5.0 $GJ/m^2/yr$
Annual rain days = 271 days/yr
Total rainfall = 1434 mm/yr

Predicted peak MAI = 34 $m^3/ha/yr$
Age at peak MAI = 20 yr

Total pan evaporation = 879 mm/yr
Soil water capacity = 272 mm
Total runoff+drainage = 741 mm/yr
Drought stress [0-1] = 0.95
Closed canopy LAI = 6.12
Light use efficiency = 0.79 gDM/MJ
Total stand water use = 695 mm/yr
Net Primary Production = 37.53 t/ha/yr

Growth:

Age (yr)	MDH (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)
3	10	6	20	7
4	12	10	46	12
5	14	15	78	16
6	16	20	114	19
7	18	24	153	22
8	20	28	196	24
9	22	32	239	27
10	23	35	279	28
11	25	38	325	30
12	26	41	367	31
13	27	43	407	31
14	29	45	451	32
15	30	47	490	33
16	31	49	528	33
17	32	51	568	33
18	33	52	604	34
19	34	54	642	34
20	35	55	680	34
21	36	56	712	34
22	37	57	747	34
23	38	59	782	34
24	39	60	810	34
25	40	61	843	34
26	40	61	874	34
27	41	62	899	33
28	42	63	928	33
29	42	64	957	33
30	43	65	985	33
31	44	65	1006	32
32	44	66	1032	32
33	45	67	1058	32
34	45	67	1083	32
35	46	68	1107	32
36	46	68	1123	31
37	47	69	1146	31
38	47	69	1167	31
39	48	70	1189	30
40	48	70	1209	30
41	49	71	1229	30
42	49	71	1241	30
43	50	72	1260	29
44	50	72	1278	29
45	50	72	1296	29
46	51	73	1313	29
47	51	73	1329	28
48	51	73	1345	28
49	52	74	1361	28
50	52	74	1368	27

SQ is Site Quality
SQ index is MDH at age 15 yrs
MDH is Mean Dominant Height
LAI is Leaf Area Index (ratio of leaf area to ground area)

Vol is the sum of all tree stem wood volumes under bark from ground to top
BA is Basal Area (cross-sectional area of all trees over bark at 1.3m high)
MAI is Mean Annual Increment of Vol

NOTE: Growth data are for an unthinned stand planted at 1000 stems/ha.
WARNING: Results shown are based on assumptions regarding input costs, revenues. Product yields from growth models may be indicative only. Professional advice should be sought before acting on any output model.

13.2 ProMod outputs for Forestier

ForestierHydrologyStudy ***E. nitens***

Location: Easting = 575043 Northing = 5243134 Aspect = E Elevation (m) = 270

Soil:
Slope % = 2
Depth (cm) = 150
Stoniness % = 50
Fertility: good natural site
Texture: well-structured clay-loam
Drainage: good drainage

Climate:

Month	Temp(max) (°C)	Temp(min) (°C)	Rainfall (mm)	Radiation ($MJ/m^2/day$)	Pan Evap. (mm)	Rain Days
Jan	20.5	10.9	60	23.5	4.5	10.0
Feb	20.8	10.8	62	19.7	4.2	9.6
Mar	19.0	9.5	71	14.2	2.9	12.1
April	16.6	7.8	81	9.6	2.0	12.5
May	13.3	5.7	84	6.1	1.2	14.5
June	11.3	3.8	89	4.9	0.7	13.1
July	10.8	3.3	87	5.7	0.8	14.7
Aug	11.5	3.8	83	8.5	1.3	15.3
Sep	13.4	4.8	64	12.8	2.2	14.3
Oct	15.5	5.7	81	17.2	2.8	14.8
Nov	16.7	7.5	74	20.0	3.5	15.2
Dec	18.5	8.8	91	22.5	4.2	13.6

Site:

SQ index (ProMod) = 30.1 m

Mean maximum temp. = 15.7 °C
Mean minimum temp. = 6.9 °C
Mean daily temp. = 11.3 °C
Total solar radiation = 5.0 $GJ/m^2/yr$
Annual rain days = 160 days/yr
Total rainfall = 928 mm/yr

Predicted peak MAI = 34 m^3/ha/yr
Age at peak MAI = 20 yr

Total pan evaporation = 918 mm/yr
Soil water capacity = 127.5 mm
Total runoff+drainage = 278 mm/yr
Drought stress [0-1] = 0.90
Closed canopy LAI = 5.50
Light use efficiency = 0.80 gDM/MJ
Total stand water use = 655 mm/yr
Net Primary Production = 37.61 t/ha/yr

Growth:

Age (yr)	MDH (m)	BA (m^2/ha)	Vol (m^3/ha)	MAI (m^3/ha/yr)
3	10	6	21	7
4	12	10	47	12
5	14	15	79	16
6	16	20	116	19
7	18	25	155	22
8	20	28	198	25
9	22	32	239	27
10	23	35	282	28
11	25	38	328	30
12	26	41	371	31
13	28	43	412	32
14	29	45	456	33
15	30	47	495	33
16	31	49	533	33
17	32	51	574	34
18	33	52	610	34
19	34	54	649	34
20	35	55	687	34
21	36	57	719	34
22	37	58	755	34
23	38	59	784	34
24	39	60	818	34
25	40	61	850	34
26	40	62	882	34
27	41	63	907	34
28	42	63	937	33
29	43	64	966	33
30	43	65	995	33
31	44	66	1015	33
32	44	66	1042	33
33	45	67	1067	32
34	46	68	1092	32
35	46	68	1110	32
36	47	69	1133	31
37	47	69	1155	31
38	48	70	1177	31
39	48	70	1198	31
40	48	71	1219	30
41	49	71	1239	30
42	49	71	1251	30
43	50	72	1270	30
44	50	72	1288	29
45	50	73	1306	29
46	51	73	1323	29
47	51	73	1340	29
48	51	74	1356	28
49	52	74	1364	28
50	52	74	1379	28

SQ is Site Quality
SQ index is MDH at age 15 yrs
MDH is Mean Dominant Height
LAI is Leaf Area Index (ratio of leaf area to ground area)

Vol is the sum of all tree stem wood volumes under bark from ground to top
BA is Basal Area (cross-sectional area of all trees over bark at 1.3m high)
MAI is Mean Annual Increment of Vol

NOTE: Growth data are for an unthinned stand planted at 1000 stems/ha.
WARNING: Results shown are based on assumptions regarding input costs, revenues. Product yields from growth models may be indicative only. Professional advice should be sought before acting on any output model.