COOPERATIVE RESEARCH CENTRE FOR **CATCHMENT HYDROLOGY**

PREDICTING THE EFFECTS OF LARGE-SCALE AFFORESTATION ON ANNUAL FLOW REGIME AND WATER ALLOCATION: AN EXAMPLE FOR THE GOULBURN-BROKEN CATCHMENTS

TECHNICAL REPORT
Report **03/5**
June 2003

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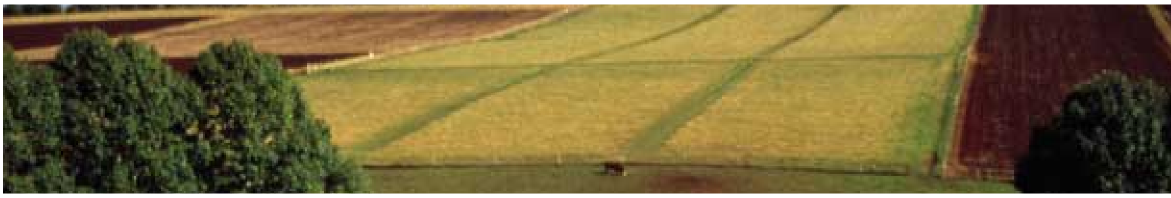

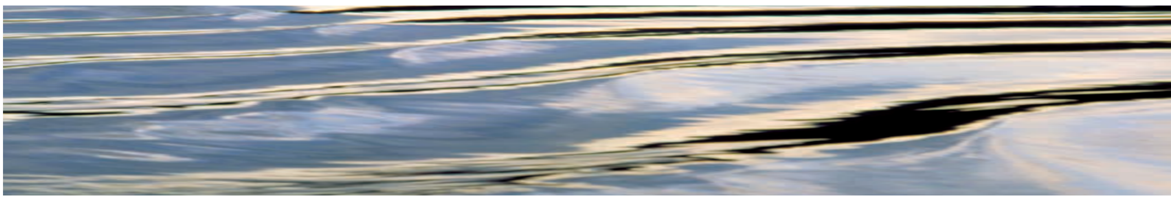

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CATCHMENT HYDROLOGY

National DRYLAND SALINITY Program

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Bibliography.

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Predicting the Effects of Large-scale Afforestation on Annual Flow Regime and Water Allocation: An Example for the Goulburn-Broken Catchments

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Preface

Trees use more water than grass. This simple statement has important implications for managing dryland salinity and changes in river flows. Until recently the data analysis and predictive tools only permitted confidence in predictions concerning river flows on a mean annual basis. This limited the use of the science in the day-to-day management of water resources and catchment planning.

This report bridges part of the gap between the science of catchment water balances and the management of catchments. The language has moved from "annual average yield" to "water security". Afforestation and water remains a contentious issue. This report sets out an important case study to underpin future decision-making.

This work has been conducted by the Cooperative Research Centre (CRC) for Catchment Hydrology's program concerning land-use impacts on rivers. The program is focused upon the impact of man's activities upon the land and stream environment upon the physical attributes of rivers. We are concerned about managing impacts for catchments ranging in size from a single hillslope to several thousands of square kilometres. The specific impacts we are considering are changes in streamflow, changes to in-stream habitat by the movement of coarse sediment and changes to water quality (sediment, nutrients and salt). If you wish to find out more about the program's research I invite you to first visit our website at http://www.catchment.crc.org.au/programs/projects/index.html.

Peter Hairsine
CSIRO Land and Water
Program Leader - Land-use Impacts on Rivers
CRC for Catchment Hydrology

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Abstract

Large-scale afforestation will result in a significant reduction in the volume of streamflow and the associated water allocations. The impact of afforestation on mean annual flow is well known, but its impact on seasonal flow or flow regime is not well understood. In the Goulburn-Broken catchments there are plans to convert large areas of pastures to forestry plantations in the coming decades. In this study we evaluate the impact of converting pasture to blue gum plantation on mean annual water yield and flow regime in the Goulburn-Broken catchment. We combined a simple mean annual water balance model with a plant growth model (3PG) to estimate the reduction in mean annual water yield and the time of maximum impact on water yield. These models have been implemented in a GIS to facilitate spatial analysis of rainfall and land-use information. The results showed that the maximum reduction in mean annual flow is 8% for Lake Eildon and 14% for Goulburn Weir if all suitable areas are planted to blue gum. However, under a moderate scenario where both social and economic factors are considered, the area of the blue gum plantation will be significantly smaller. As a result, reduction in mean annual flow is 2% at Lake Eildon and 4% at Goulburn Weir. We also investigated the effect of plantations on flow regime by linking flow duration curve analysis with data from paired catchment studies. It was found that plantations would significantly reduce low flow and hence increase flow variability. When combined with the system simulation model for Goulburn, it was predicted that the fraction of time water allocations are less than 100% increases from current 3% to 7% under the maximum plantation scenario. The model also predicted that unregulated flows would decrease by 6% and 27% under the moderate and maximum scenarios, respectively. The results from this study provide catchment and resource managers with useful insights into the hydrologic impacts of afforestation.

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1. Introduction

There are major plans underway to significantly increase the area of plantations in Australia (Department of Primary Industries and Energy, 1997). These plans were motivated by a range of commercial and environmental considerations (Vertessy *et al.,* 2000). For instance, large-scale afforestation is regarded as an effective option for controlling dryland salinity. However, it is now generally established that large-scale afforestation development can significantly alter hydrologic regime and thus affect water allocation. The most noticeable hydrologic response following large-scale afforestation will be reduction in mean annual flow. This annual response can be predicted easily using a catchment water balance model (Zhang *et al*., 2001). Afforestation can also affect the seasonal distribution of runoff or flow regime, but predicting the seasonal impact proves to be a more difficult task (Best *et al*., 2003). The Goulburn-Broken Catchment covers 17% of Victoria and supports a population of 250,000 people. It generates over 15% of the total state stream flow. As a major water supplier to the Goulburn-Murray Irrigation District, stream flow along the Goulburn River has been highly regulated. Water is also diverted from the catchment to service western Victoria for irrigation, stock and domestic water supplies. Agriculture and associated secondary industries are the major activities in the catchment, and the region generates about $1.5 billion of food products annually. A catchment management strategy has been developed by the Goulburn-Broken Catchment and Land Protection Board to improve the region's productivity while maintaining social well being, and environmental quality.

The Goulburn-Broken Catchment was once mostly forested, but much of the deep-rooted native vegetation has been replaced with annual pasture and cereal crops. Native vegetation has been retained in the mountainous areas in the south of the catchment. This major land-use change has modified the hydrological regime of the catchment and contributed to environmental degradation. For example, it is estimated that within the catchment there are about 4500 ha of salt discharge areas, which are expanding at around 5% per year (Goulburn Broken Catchment Management Authority, 1998). As a result, the catchment exports on average 180,000 tonnes/yr of salt to either the irrigation region or the Murray River. Key issues that concern catchment managers, irrigators and the local community are water quantity, allocation, quality and river restoration.

To address the issues of dryland salinity in the catchment, a number of land-use options have been proposed including the establishment of southern blue gum plantations (Centre for Land Protection Research, 2000). While plantations have been identified as having many environmental benefits, little consideration has been given to the possible adverse consequences of large-scale plantation expansion. These include reduction in catchment water yield and reliability of water supply (Vertessy and Bessard 1999, Vertessy *et al*., 2000, Bradford, *et al*., 2001). A number of studies have shown that stream flow from a forested catchment is generally lower than that from a grassed catchment with the same climatic conditions because forests have higher evapotranspiration rates (Holmes and Sinclair, 1986, Turner, 1991, Zhang *et al*., 2001). The key factors controlling evapotranspiration include rainfall interception, net radiation, advection, atmospheric turbulence, leaf area and plant available water capacity. The relative importance of these processes depends on climate, soil and vegetation conditions. It is important to understand the water balance-vegetation relationships through the different parts of the landscape to ensure that the negative hydrologic effects of large-scale plantation expansion can be anticipated and planned for.

The major aim of this study is to predict the changes in water yield as a result of blue gum plantations in the upper part of the Goulburn-Broken catchment. The model used in the analysis was developed by Zhang *et al*. (2001) and implemented into a GIS framework by Bradford *et al.* (2001) and substantially modified during this work. It incorporates the effects of tree age on water use estimated from the 3PG plant growth model (Landsberg and Waring, 1997). The specific objectives of this study relate to the proposed conversion of pastures to blue gum plantations and subsequent changes in hydrologic regime, including:

- Predicting mean annual water yield reduction and its spatial distribution.
- Estimating the time to maximum water yield reduction.
- Modelling the changed seasonal water yield and water supply system allocation.

2. Catchment Description and Modelling Methods

2.1 Catchment Description and Data

The Goulburn-Broken catchment consists of the catchments of the Goulburn and Broken Rivers (Figure 1). The Broken River joins the Goulburn River near Shepparton and the Goulburn then joins the Murray River upstream of Echuca. The Broken Creek, an effluent of the Broken River, joins the Murray River upstream of Barmah. The Goulburn River catchment covers an area of 16,191 km^2 with a mean annual flow of 3,000 GL at Goulburn Weir. Rainfall varies significantly from greater than 1,600 mm per year in the south-eastern high country to less than 450 mm per year in the far north of the catchment (Figure 2). The Broken River catchment covers an area of 7,723 km^2 and it joins the Goulburn River south of Shepparton. The mean annual flow is 325 GL and average annual rainfall is about 1,200 mm in the south of the catchment and decreases to less than 500 mm in the north west (Figure 2). Major land-use units in the Goulburn catchment include native vegetation (34%), dryland agriculture (58%), irrigated agriculture (7%), plantation and other (1%). Major land-use units in the Broken catchment are similar, but with a lower percentage of native vegetation (15%) and a higher percentage of plantations (2%).

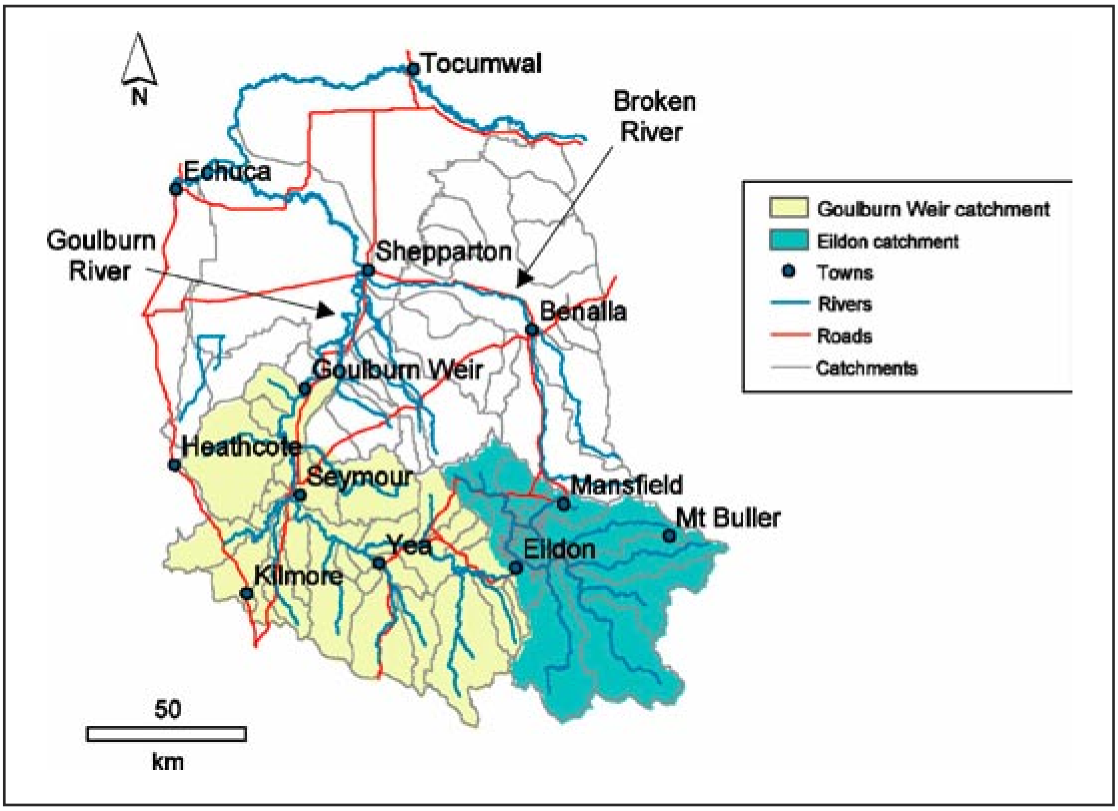

Figure 1. Location map of the Goulburn-Broken catchments, highlighting the major catchments used in the study.

The catchment boundaries (Figure 1) were determined from a 25m digital elevation model (DEM) provided by the Department of Natural Resources and Environment, Victoria (NRE). Long-term average annual rainfall for the period of 1961 – 1990 was used in the study. The rainfall data was calculated from mean monthly rainfall surfaces obtained from the Bureau of Meteorology at 2.5 km spatial resolution (Figure 2). A generalized tree cover map was provided by the Murray Darling Basin Commission (Ritman, 1995) and is shown in Figure 3. All the spatial inputs were resampled to 100 m grid resolution for analysis. Measured stream flow at 16 gauged sub-catchments was used to validate the water balance model. These catchments are defined by their contributing areas upstream of selected gauging stations (see Figure 4). Monthly stream flow data for a number of selected gauging stations were provided by Thiess Environmental Services. The period of stream flow data mostly coincided with the period of the rainfall data. However, in the worst case, the overlapping period of record is 5 years.

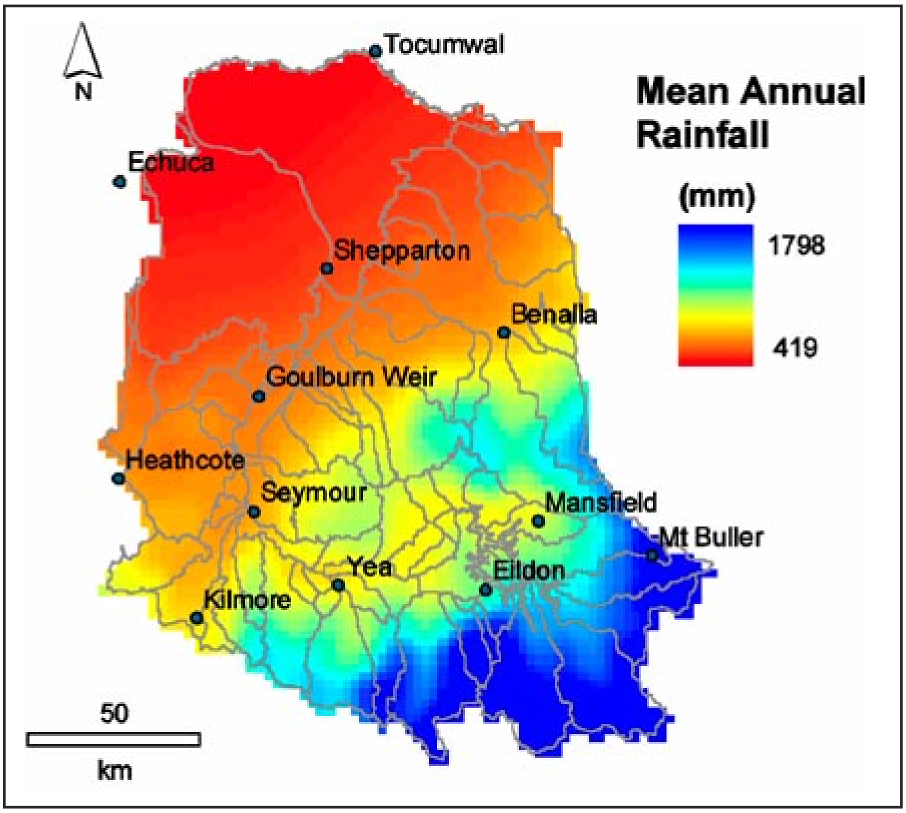

Figure 2. Long term mean annual rainfall distribution for the Goulburn-Broken catchment (source: BOM, 2000).

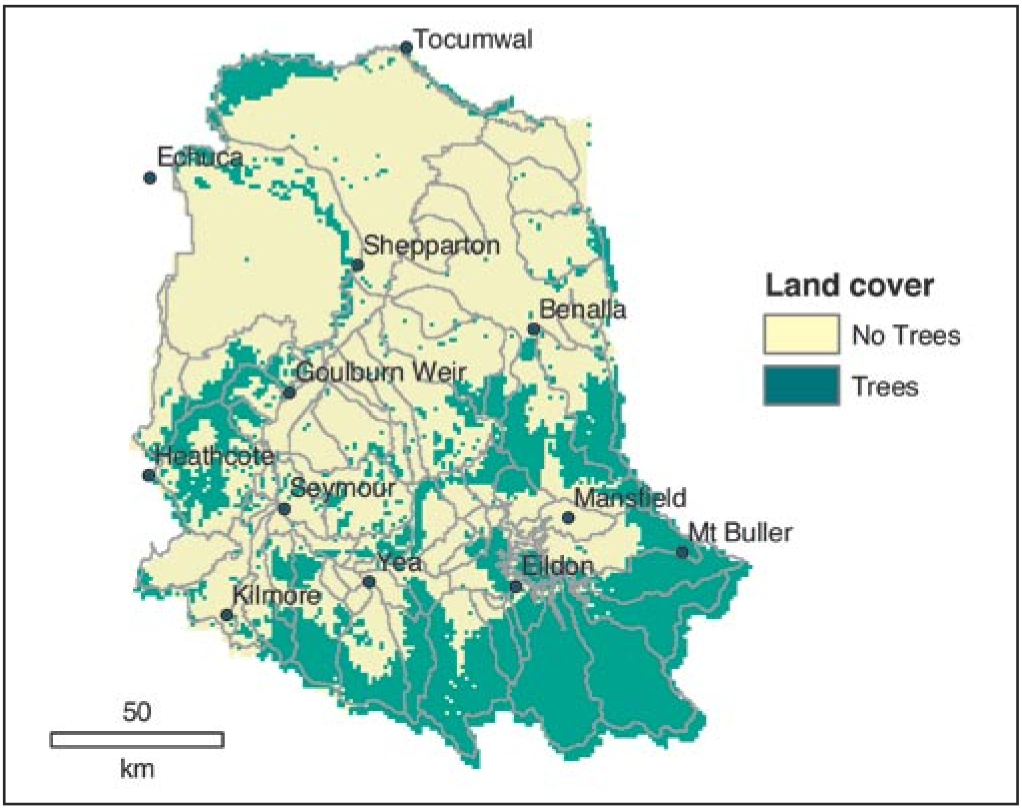

Figure 3. Map of current tree cover in the Goulburn-Broken catchments (Ritman, 1995).

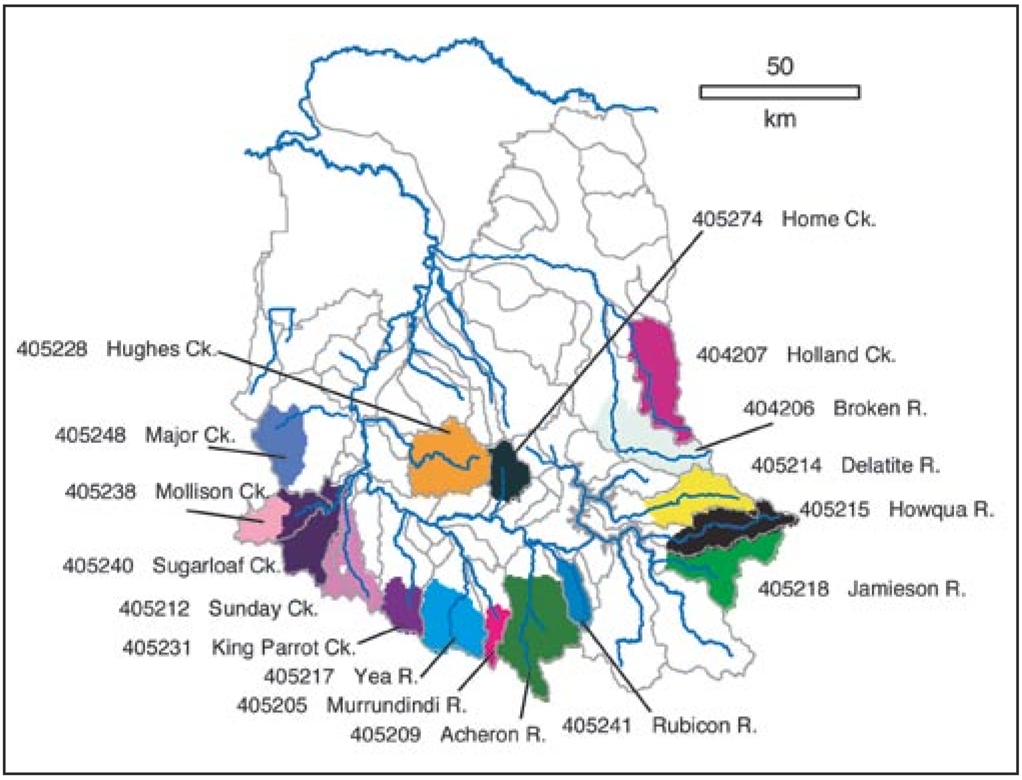

Figure 4. Location of the 16 gauged catchments used in this study for model validation.

2.2 Mean Annual Water Balance Model and Inputs

The water balance model used in this study was developed by Zhang *et al.* (1999, 2001). It calculates mean annual evapotranspiration from mean annual rainfall and potential evapotranspiration (Figure 5). In estimating catchment average water yield, it is assumed that there is no net change in catchment water storage over a long period of time. As a result, catchment water yield can be calculated as the difference between long-term average rainfall and evapotranspiration. The average relationships are shown in Figure 6 for grassland and forested catchments.

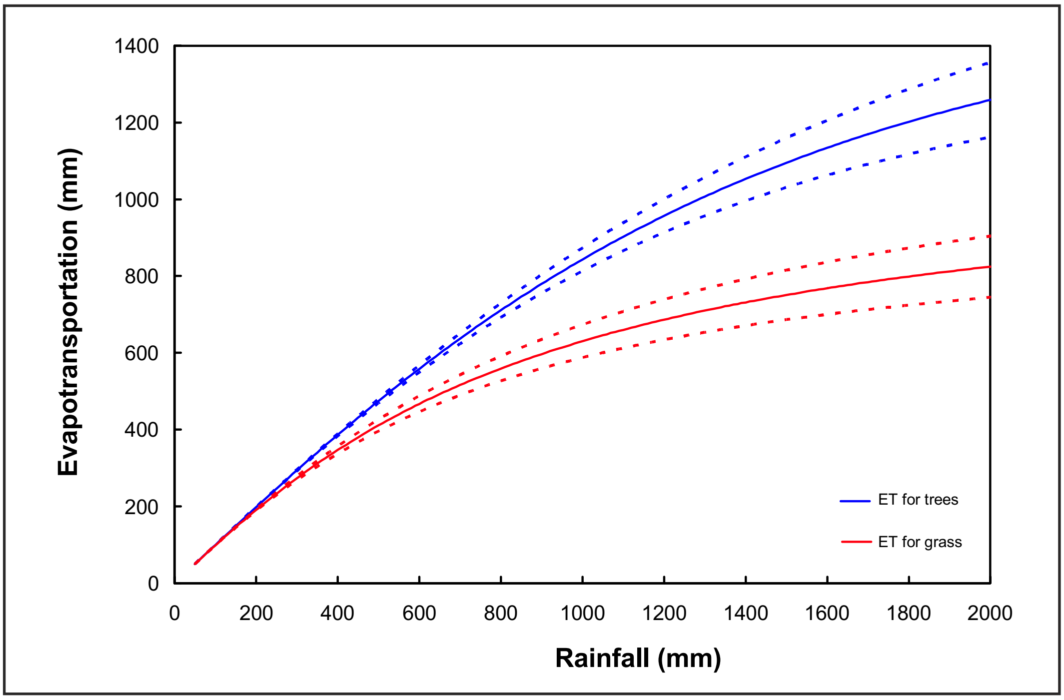

Figure 5. Relationships between mean annual evapotranspiration and rainfall. Solid lines indicate average annual evapotranspiration and dotted lines represent ±2STD, where STD is standard deviation.

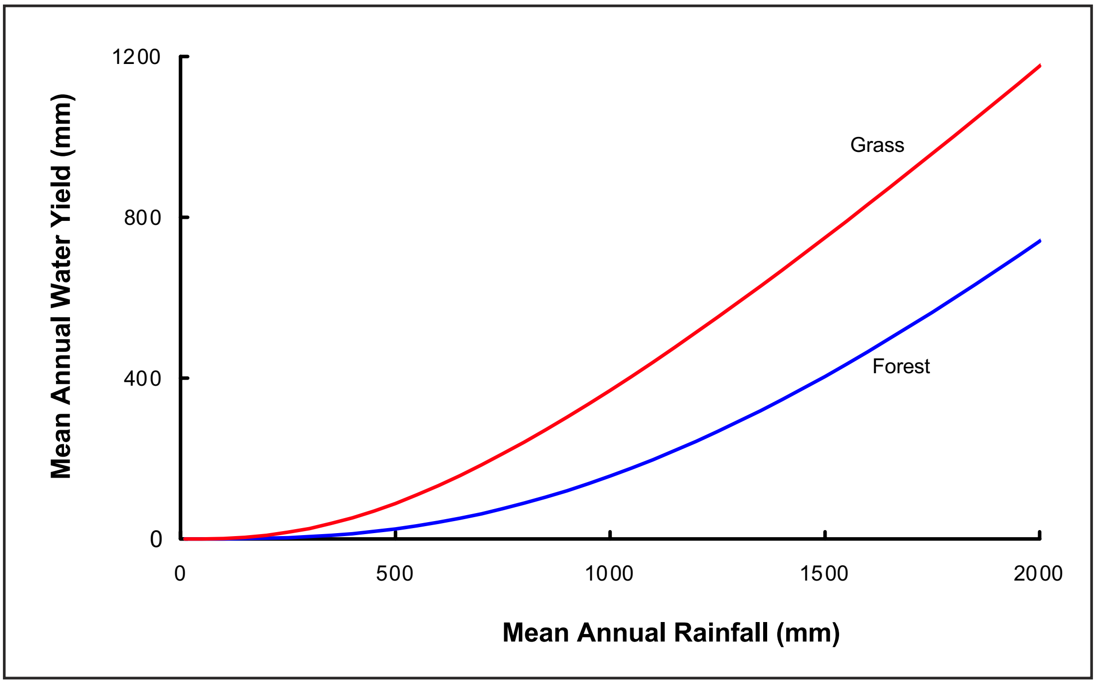

Figure 6. Relationships between mean annual water yield and rainfall.

The water balance model was implemented in the ArcInfo Geographic Information System (GIS). Three key datasets were required to calculate evapotranspiration: catchment boundaries, long term mean annual rainfall and percent forest-cover in a catchment. Estimated evapotranspiration was then subtracted from the long-term mean annual rainfall to provide the calculation of water yield. To investigate the change in water yield, each scenario required a different forest-cover input, while the catchment boundaries and rainfall surface data remained constant.

2.3 Implementation of the Mean Annual Water Balance Mode into GIS Framework

The relationships underpinning the Zhang model was based on the proportions of tree and non-tree area and long term mean annual rainfall over the whole catchment. Bradford *et al.* (2001) implemented this model into a GIS framework based on this consideration. In that approach, rainfall was averaged across the catchment and the proportions of treed and non-treed area were calculated and these catchment-averaged numbers were input into the model.

An alternate implementation of the model used the characteristics of each cell, i.e. percentage tree cover and the long term mean annual rain for that cell (Vertessy and Bessard, 1999). An argument for the latter is that it accounts for spatial variability in vegetation and rainfall, although it does not necessarily comply with the philosophy behind the relationship. This is because the original relationship is based on mean tree cover and mean rainfall for whole catchments. For the 'cell' based approach, the vegetation status of each cell is input to the appropriate function with the rainfall for that cell. The resulting values are then averaged for each catchment. This method, which applies unmodified inputs to the model and averages the outputs, has the advantage that the intra-catchment variability is considered. In this study, we used this 'cell' based approach.

2.4 Linking the Mean Annual Water Balance Model with a Plant Growth Model (3PG)

The water balance model developed by Zhang *et al.,* (2001) can be used to predict the effects of afforestation on mean annual water yield. However, the model does not consider seasonal variability in water yield and the upper set of curves (for trees) in Figure 5 represents water use or evapotranspiration for well-established plantations. It is known that the impact on water yield changes with the age of the trees and the time to maximum water yield reduction varies depending on climate and soil conditions. The maximum water yield reduction is not always attained in plantations due to management practices, for example, thinning and harvesting. An attempt was thus made to relate water yield reduction with plantation age and site suitability using a plant growth model (3PG) (Landsberg and Waring, 1997). A recent literature review showed that the impact of afforestation on annual water yield can be predicted based on forest age, species and site suitability (Best *et al.,* 2003).

3PG is a process-based model that predicts monthly net photosynthesis by forest stands from climate, soil and management factors. The model requires monthly values of rainfall, radiation, vapour pressure deficit (VPD), wind speed, maximum air temperature and minimum air temperature. The model also utilizes soil properties to estimate available water storage. The predicted monthly carbon fixation is allocated to foliage, stems and roots using allometric relations of biomass to tree diameter. Stem carbon is converted to wood biomass and, with an allowance for branches and bark, to an estimate of stemwood volume production. Monthly water use is calculated using the Penman-Monteith equation (Monteith, 1981) with a monthly mean canopy conductance estimate which takes into account the effects of leaf area, vapour pressure deficit, soil moisture stress, salinity, temperature and tree age.

The spatial version of 3PG applied in this study (called "spatial 3PG" here) applies these calculations to each cell of a 0.01 degree grid of the area, using a climate grid file derived from ANUCLIM (Houlder *et al.,* 1999). Model output consists of a set of GIS-compatible ASCII grids of predicted values for the selected output variables at user specified stand ages.

Spatial 3PG was applied to the Goulburn-Broken catchment, using species parameters for *Eucalyptus globulus* determined in a previous study (Morris, 1999). Growth predictions were extracted at 5-year intervals up to a maximum stand age of 25 years, since the parameterisation is based on young trees and may be unreliable in older stands. Attributes estimated at each interval were stand volume, mean annual stem growth increment and leaf area index (LAI). The effects of LAI on plant water use or evapotranspiration can be assessed using the following relationships:

$$ET = \begin{cases} ET_{+2STD} & LAI \geq 0.5 * \Delta LAI_1 + LAI_{medium} \\ ET_{medium} & 0.5 * \Delta LAI_1 + LAI_{medium} > \text{LAI} \geq LAI_{medium} - 0.5 * \Delta LAI_2 \\ ET_{-2STD} & LAI < LAI_{medium} - 0.5 * \Delta LAI_2 \end{cases}$$

where ET_{medium} is the average evapotranspiration shown in Figure 5, ET_{+2STD} is the evapotranspiration for two times standard deviation (95% confidence interval) above the mean, ET_{-2STD} is the evapotranspiration under two times standard deviation (95% confidence interval) below the mean, and LAI_{medium} is the LAI for a medium site, ΔLAI_1 is the difference in LAI between a good site and a medium site, ΔLAI_2 is the difference in LAI between a medium site and a poor site.

2.5 Estimating the Seasonal Impacts of Plantations on Water Yield

While change to mean annual water yield is important, the impacts of plantations on seasonal flows can be more significant from both environmental and extractive water use perspectives. However, understanding of the seasonal impacts is still very limited and there are no effective tools available for quantifying the impact. A commonly used approach for making such predictions is to rely on detailed physically based models or statistical models derived from paired catchment studies (Sivapalan *et al.,* 1996; Scott and Smith, 1997). However, use of physically based models in large catchments is problematic because of data availability. Therefore, in this study, prediction of the seasonal impact was performed using data obtained from paired catchment studies.

Paired catchment studies revealed that plantations can affect total flow and low flow differently (Scott and Smith, 1997). One way to evaluate this effect is to examine changes in the flow duration curve (FDC). An FDC represents the relationship between the magnitude and frequency of stream flow for a catchment (Figure 8). It provides an estimate of the percentage of the time a given flow was equalled or exceeded. Use of FDCs to examine changes in flow regimes requires local paired catchment data and some generalization of the response. We used the data from Pine Creek, a tributary of Sunday Creek, within the Goulburn River catchment. The catchment area is 320 ha (3.2 km^2) and was open grassland prior to 1987, when the whole catchment was planted to pinus radiata. Flow from the catchment was monitored from 1988 onwards to quantify changes in hydrological process as a result of the tree planting. Linke *et al.,* (1995) provide a detailed description of the catchment characteristics and data availability.

Estimation of afforestation impacts on flow regime at Goulburn Weir requires a regional FDC which represents flows at Goulburn Weir and average flow characteristics of contributing catchments. Given that Lake Eildon is highly regulated, flows from catchments above Lake Eildon were excluded. For this purpose, a synthetic FDC for Goulburn Weir was calculated in a three step process. Firstly, three sub-regions contributing to the Goulburn Weir flow were identified from FDCs for a number of catchments in the area under different land-use conditions (Figure 7). Secondly, a typical FDC for each sub-region was calculated using available observed flow data (Figure 8). Finally, sub-regional FDCs were averaged to form the current regional Goulburn Weir FDC (Figure 8).

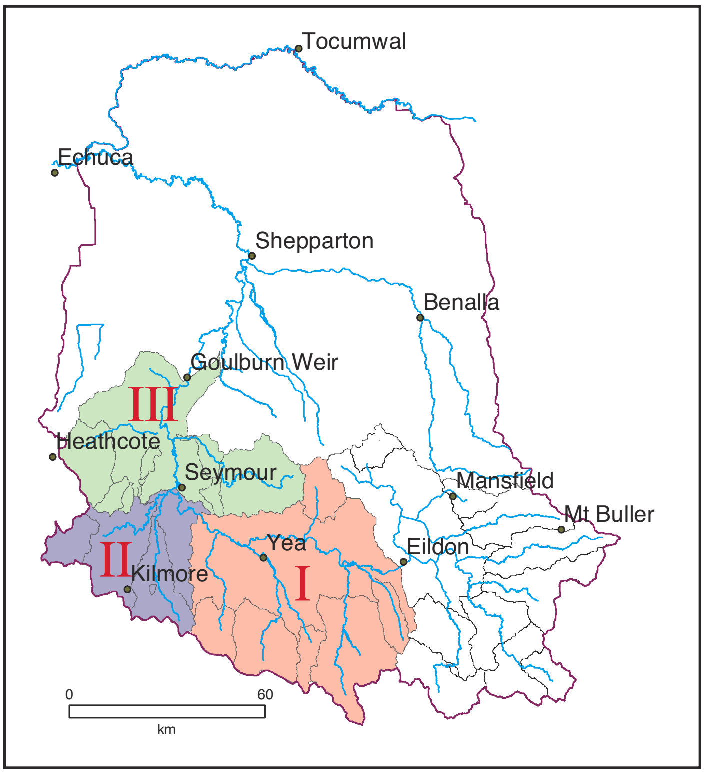

Figure 7. Location of the three sub-regions within the Goulburn-Broken catchments.

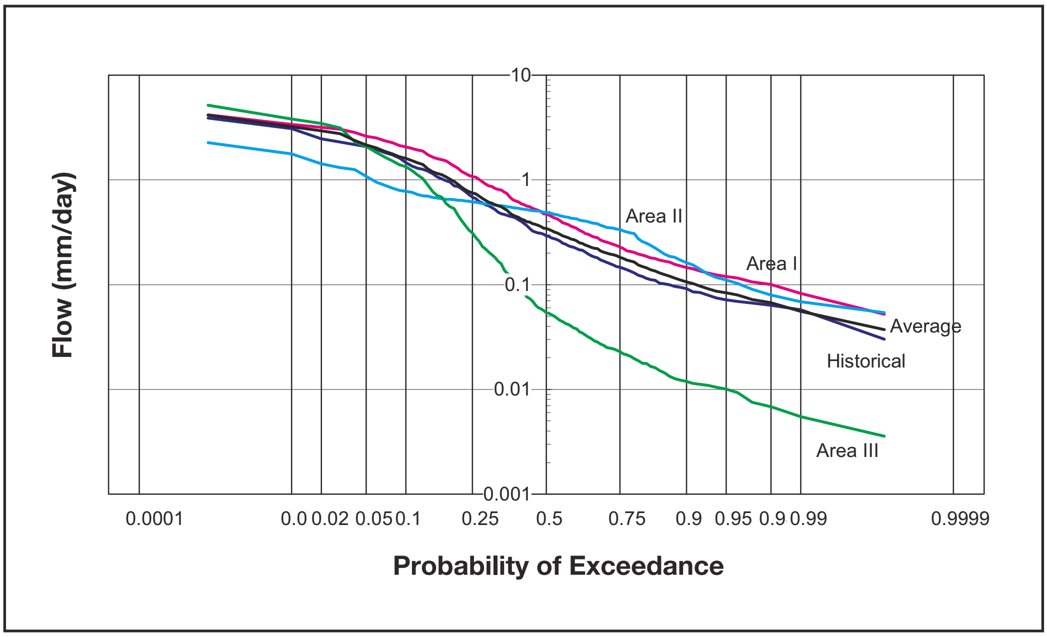

Figure 8. Average FDC at Goulburn Weir derived from three sub-regions below Eildon Dam.

Based on the monthly FDC from Pine Creek, a simple method was developed which reflects the changes in monthly flow after afforestation in the catchment. This method assumes that the total reduction in seasonal flow can be characterised by a combination of a proportional reduction and a constant reduction in flows. Thus, the proportional reduction will have a greater effect for high flows than for low flows, and the constant reduction will have greater impact on low flows than high flows. The method was applied to the three regions to predict FDCs for changed land-use conditions. Firstly, mean annual water yield under changed land-use was calculated for each of the three regions using the water balance model described in Section 2.2. Then the method was used to redistribute the total water yield reduction to reflect seasonal changes in flow. This is described in the following steps:

- Quantify the effect of afforestation on percentile flows using data from Pine Creek involving calibration of the following model:

  $$Q_{new\%} = a*Q_{current\%} - b \quad (mm/d) \qquad (1)$$

  where $Q_{new\%}$ is the percentile flow for changed landuse, $Q_{current\%}$ is the percentile flow for current land-use. The first term ($a*Q_{current\%}$) in Eq. (1) represents the proportional reduction in flows and the second term (b) is the constant reduction in any given flow. For Pine Creek catchment, $Q_{current\%}$ is the monthly flow during the period of 1989-1991, while $Q_{new\%}$ is the monthly flow for the period of 1998-2000.
- Create a typical normalized FDC for each area (I,II,III) by averaging the normalized local FDCs from each sub-catchment. This involves ranking the stream flow data and normalizing the flow by average flow.
- For each region convert the typical normalized FDC into dimensional form (mm) using average flow for those regions ($\overline{Q}_{current}$).
- Estimate mean annual average flow under changed land-use ($\overline{Q}_{new}$) using the relationships shown in Figure 6.
- Apply Eq. (1) to each region and optimize the model parameter a so that the calculated average flow for the new FDC equals the mean annual average flow under changed land-use ($\overline{Q}_{new}$). It was assumed that coefficient b in Eq. (1) is a constant.

3. Impact of Blue Gum Plantations on Water Yield: Scenario Modelling

The ultimate goal of this study was to predict the impact of major future land-use changes (i.e. blue gum plantations) on catchment water yield and water allocation. Three scenarios were considered for the catchment and the impact on water yield was evaluated for Lake Eildon and Goulburn Weir. The scenarios modeled in this study are defined as:

- *Maximum* Scenario – 100% adoption rate for the two most suitable classes
- *Moderate* Scenario – variable adoption rate proportional to suitability classes
- *Low* Scenario – 10% adoption rate for the two most suitable classes.

3.1 Maximum Scenario: Blue Gum Plantation Establishment on all Suitable Land Currently not Forested

To investigate the impact of possible future land-use changes on catchment water yield, scenarios were derived from plantation suitability data developed by the Centre for Land Protection Research (2000). These datasets were generated from land suitable for sustaining plant growth based on the most limiting factor (MLF) method. The biophysical criteria used to generate these data included rainfall, temperature, slope and soil characteristics. In our study, we considered specifically the impact of a southern blue gum (*E. globulus spp globulus*) plantation on catchment water yield because it is the most economically attractive species for the region (Trapnell *pers. com.*). Areas identified as suitable for blue gum plantations are shown in Figure 8. Classes 1 and 2 were considered suitable and assigned 100% adoption rate. It should be noted that the areas shown in Figure 9 represent the maximum likely extent of plantations and is thus likely to be a worst case scenario.

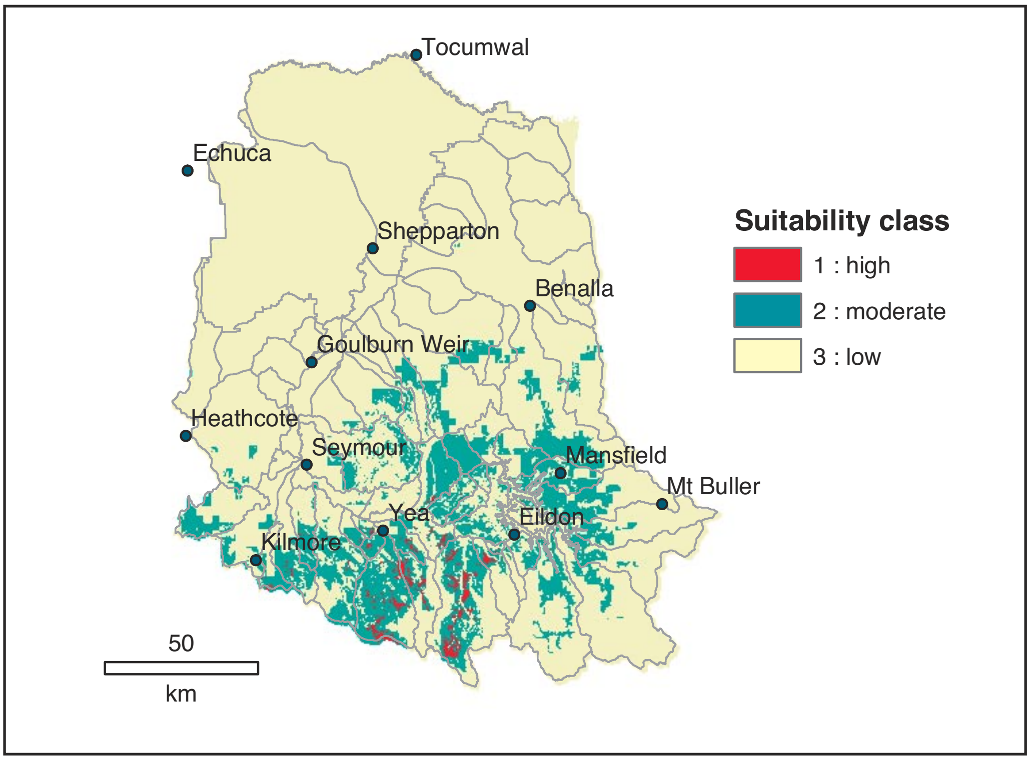

Figure 9. Southern Blue gum suitability map using the most limiting factor (MLF) method Class 1 and 2 are considered as suitable and Class 3 is not.

(source: Centre for Land Protection Research, NRE, 2000).

3.2 Moderate Scenario: Blue Gum Plantation Establishment at Variable Adoption Rates

Plantation development is not only influenced by biophysical but also social and economic factors. Hence, the area that will be planted to trees will be far less than the area deemed suitable for plantation in Figure 9 above. In this scenario, the effect of those other factors was estimated as a consensus of expert opinion. The maximum plantation area is scaled down based on the likelihood of adoption rate. Under this scenario, adoption rates for suitability classes 1, 2 and 3 are 50%, 25% and 0% respectively. It assigns the proportion of each of the 'suitable' cells that will become plantation under the scenario.

3.3 Low Scenario: Blue Gum Plantation Establishment at Low Adoption Rates

A popular view held was that 50% and 25% adoption rates were still optimistic.

For the *low* adoption rate scenario these rates for suitability classes 1, 2 and 3 were reduced to 10%, 10% and 0% respectively.

3.4 Impact of Blue Gum Plantation Establishment on Seasonal Water Allocation

To assess the impact of blue gum plantations on water allocation in the catchment, it is necessary to obtain time series of monthly flow under changed land-use conditions. This was done by combining time series of monthly flow under current land-use conditions with FDCs under pre and post land-use change conditions. This method was initially developed by Hughes and Smakhtin (1996) to extend streamflow data.

The method uses FDCs to translate pre land-use change flows to post land-use change flows, starting with time series of monthly flow at Goulburn Weir under current land-use conditions. The flow data are then described by a FDC. The method described in Section 2.5 is then used to obtain a post land-use change FDC. Finally, a time series of monthly flow under post land-use change conditions is generated. The procedure is illustrated in Figure 10.

The procedure is designed to predict the distribution of monthly flows under changed land-use conditions (specifically afforestation). However, it should be noted that the method may not accurately reflect the time series of flows because it does not explicitly consider serial correlations in monthly flows. Nevertheless, this procedure should produce a time series of monthly flow data of quality consistent with that of the mean annual water balance model. It should also be noted that information contained in FDCs, i.e. percentile flows and their exceedance probability are simple but useful statistics that are likely to be used by catchment managers.

The impacts on water supply and unregulated environmental flows of changed Goulburn Weir and Lake Eildon inflow (ie, catchment runoff) were analysed. This was done by routing the monthly flow derived for post land-use change conditions through Goulburn-Murray Water's system simulation model of the Goulburn System (GSM). GSM output includes monthly time series of regulated deliveries, diversions, seasonal allocations, reservoir spills and pre-releases. These parameters will characterise the principal effects of the changed inflows.

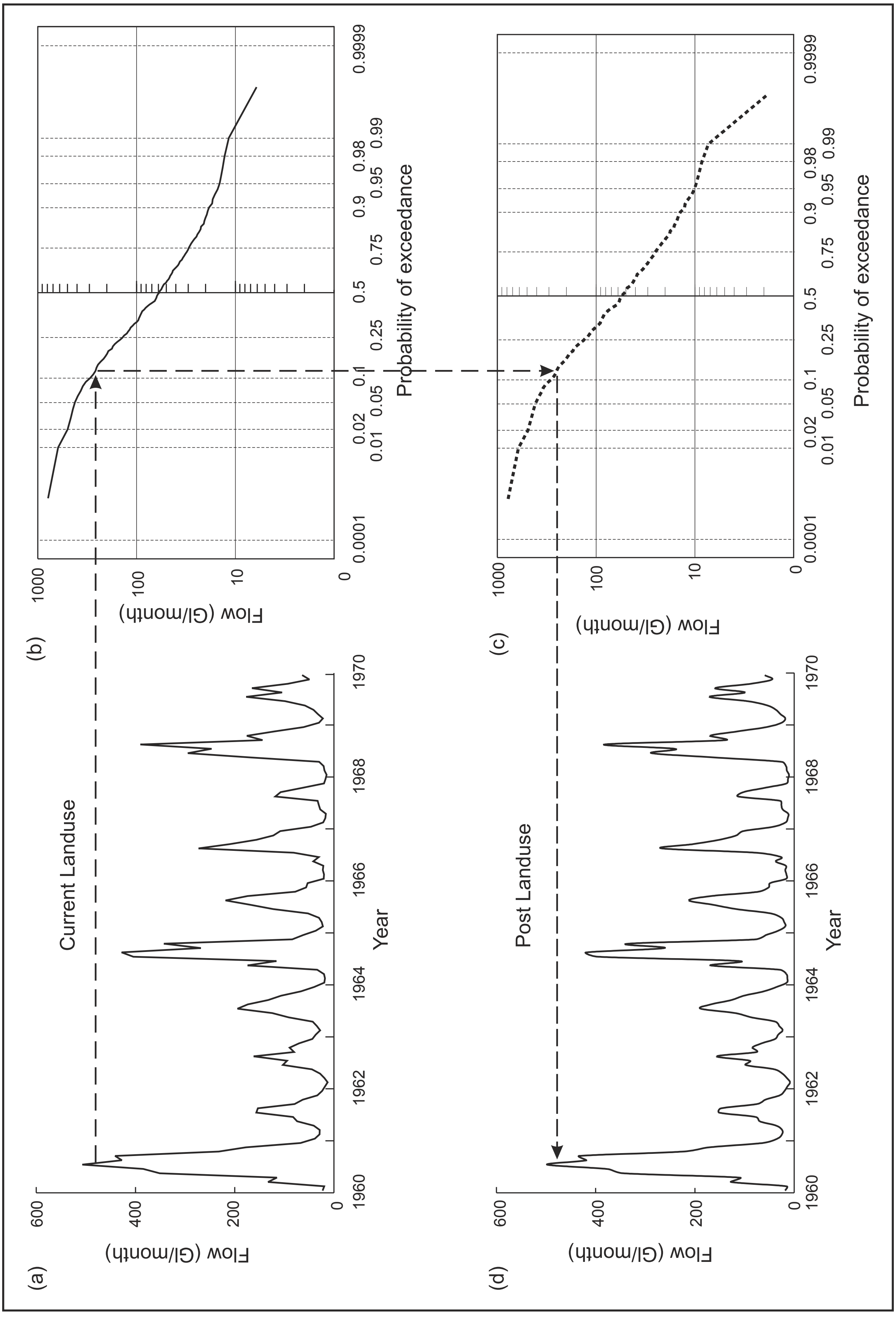

Figure 10. Illustration of monthly flow generation under post land-use change conditions using monthly FDCs.

4. Results

4.1 Model Validation Against Measured Stream Flow

The performance of the model under current vegetation conditions was evaluated by comparing model estimates of mean annual water yield against measured mean annual stream flow. This is a necessary step in predicting the effects of future afforestation on water yield and it provides a measure of confidence in how well the water balance model holds for the catchment.

Figure 11 shows a comparison between modelled and measured mean annual water yields for these catchments. The slope of the regression through the origin is 1.04 with a correlation coefficient of 0.8. Since the main interest is in flow to Lake Eildon and Goulburn Weir, model estimates were compared with measured flow at these locations. The difference between modelled and measured flow is 7% and 3 % respectively.

4.2 Impact of Blue Gum Plantations on Mean Annual Water Yield

4.2.1 Plantation Water Use and Time to Maximum Impact

Results from 3PG modeling showed large spatial variations in blue gum productivity expressed as stand volume (Figure 12). On a good site, stand volume reached a maximum value of 28 m^3 per hectare after 10 years of growth, on a medium site, the maximum value is 23 m^3 per hectare after 15 years, where the maximum stand volume on a poor site, is only 15 m^3 per hectare after 20 years (Figure 12). In order to estimate relative water use of blue gum plantations at different sites and the time of maximum water use, leaf area index (LAI) was also modelled by 3PG. Similar to stand volume, LAI also showed a large variability (Figure 13). Values of LAI over time are shown in Figure 13 for three selected sites in the catchment and they vary from 2.6 to 4.4. It is clear that the time to maximum LAI is dependent upon site suitability and varies between 8 to 16 years. The results can be used to indicate relative differences in plant water use and the time of maximum impact on catchment water yield.

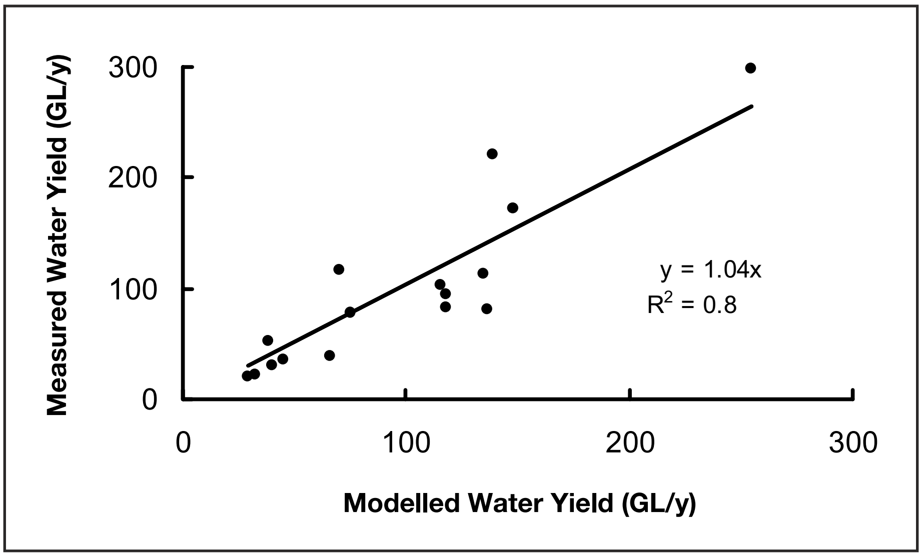

Figure 11. Comparison between modelled and measured mean annual water yield for 16 gauged catchments in the Goulburn-Broken region.

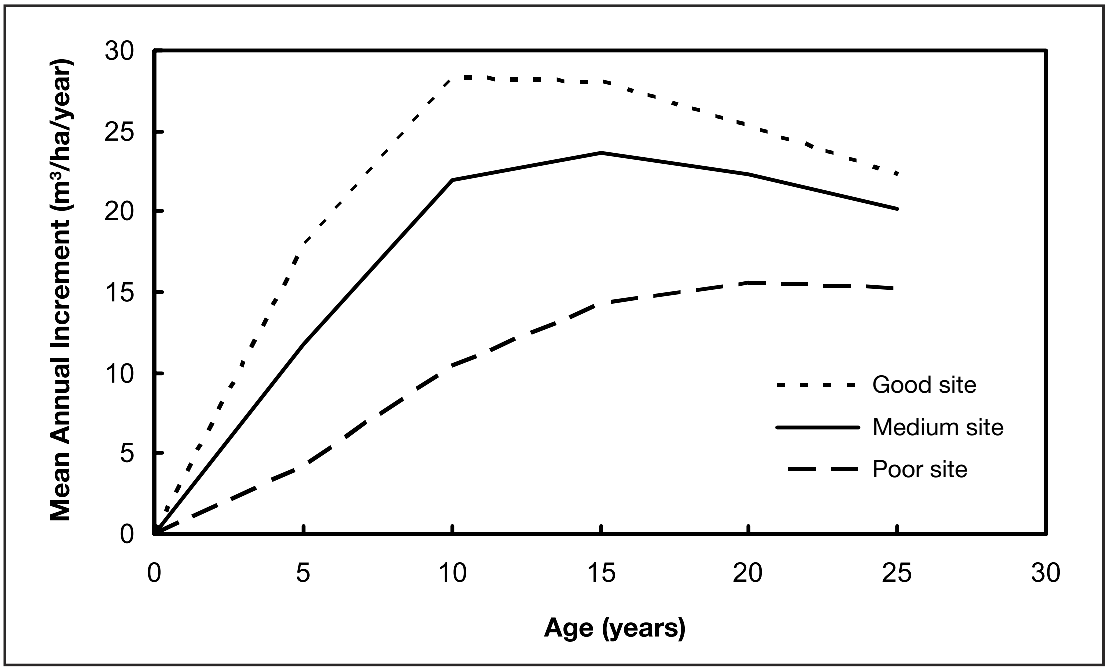

Figure 12. Mean annual increment in stand volume modelled by 3PG for the upper part of the Goulburn-Broken catchments.

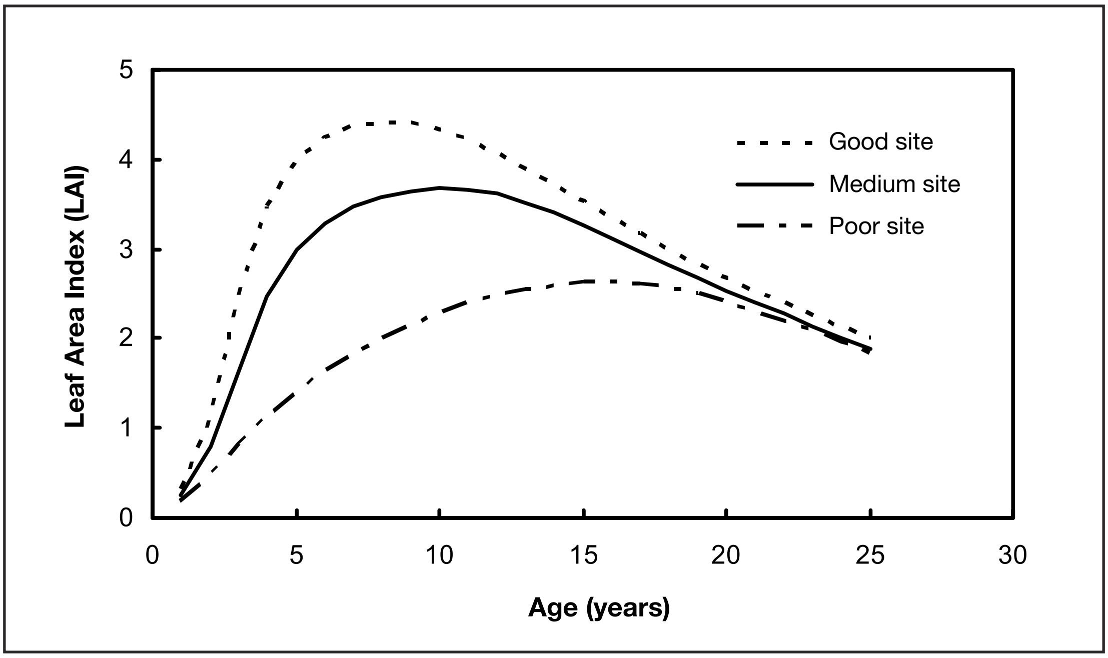

Figure 13. Leaf area index (LAI) modeled by 3PG for the upper part of the Goulburn-Broken catchments.

If we assume the time of maximum impact on water yield coincides with maximum LAI, then we can conclude that it will take 8 to 16 years for blue gum plantation to reach its maximum water use and hence maximum reduction in water yield.

4.2.2 The Impact of Blue Gum Plantation Establishment on Water Yield Under the Maximum Scenario

In this scenario, it was assumed that 100% of the areas suitable for blue gum become plantations (Figure 9). This represents an increase in forest cover of 618 km^2 or 16% of the total catchment area above Lake Eildon and 2246 km^2 or 21% of the total area above Goulburn Weir (including Lake Eildon). It is clear that water yield reduction shows large spatial variation (Figure 14). The unit reduction in mean annual water yield varied between 0 and 150 ML/km^2. The greatest reduction occurred in catchments with the most suitable land between Seymour and Eildon. The least change in water yield occurred in catchments around Goulburn Weir and in the wettest catchments above Lake Eildon that have snowfall complications.

The maximum impact of southern blue gum plantation on inflow to Lake Eildon was investigated by aggregating the effects of the plantation on water yield in the catchments above Lake Eildon. For the *maximum* scenario, the predicted mean annual flow to Lake Eildon will be reduced by 113 GL per year, which is about 8% of the current mean flow to the lake. For catchments above Goulburn Weir (including Eildon catchments), the predicted reduction in mean annual flow is 400 GL per year or 14%.

It should be noted that these reduction estimates represent the worst case scenario from a water yield point of view. Since there are economic and social factors that will limit the adoption rates of blue gum plantations, it is unlikely that all areas suitable for blue gums will be planted at any one time.

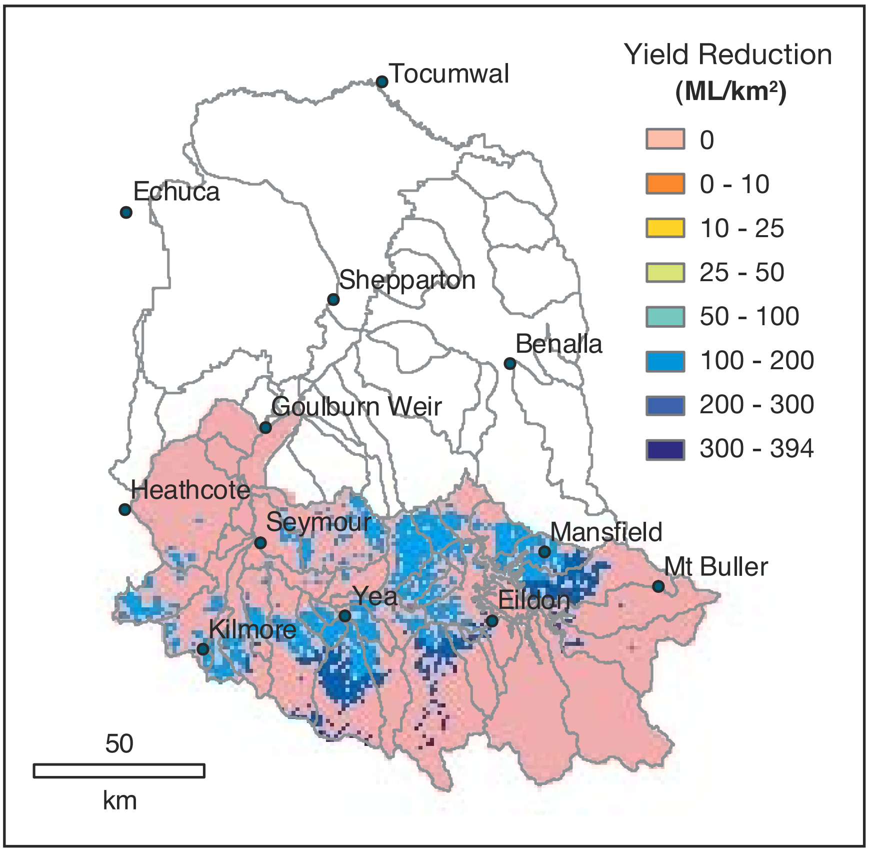

Figure 14. Maximum reduction in water yield or stream flow if all suitable areas became blue gum plantations.

4.2.3 The Impact of Blue Gum Plantation Establishment on Water Yield Under the Moderate Scenario

In the *moderate* scenario, a more realistic adoption rate determined by other factors was considered. For this moderate adoption scenario, it represents an increase of 154 km^2 or 4% of the total area above Lake Eildon and 612 km^2 or 5.8% of the total area above Goulburn Weir. Reductions in catchment water yield predicted to occur in this scenario are shown in Figure 15. The overall reduction is much less than predicted for the worst case (*maximum*) scenario. The estimated mean annual reduction in flow is 27 GL per year or 2% for Lake Eildon and 105 GL per year or less than 4% for Goulburn Weir.

4.2.4 The Impact of Blue Gum Plantation Establishment on Water Yield Under the Low Scenario

In the *low* adoption scenario, where suitability classes 1 and 2 were assigned an adoption rate of 10%, plantations represent 1.6 % of the total area above Lake Eildon and 2.1% for Goulburn Weir. The estimated reduction in mean annual water yield is 3 GL per year or 1% for Lake Eildon and 56 GL per year or 2% for Goulburn Weir.

4.3 Impact of blue gum plantation establishment on annual flow regime

The analysis described above is based on long-term average annual rainfall and stream flow. While information on mean annual water yield change is useful, it is sometimes more useful to predict the impact of plantation on seasonal flows. For example, dry-seasonal flow is of concern for water resource managers because it coincides with periods of greatest demand.

Daily FDCs at Pine Creek for the periods of 1989-1991 and 1998-2000 are shown in Figure 16a. We assumed that flow for the period of 1989-1991 represents flow under pre-treatment conditions (i.e. grass) because the trees were very small then. It is clear that percentage reduction is much greater for low flows than for high flows. It should be noted that the FDCs at Pine Creek were affected by both landuse change and rainfall

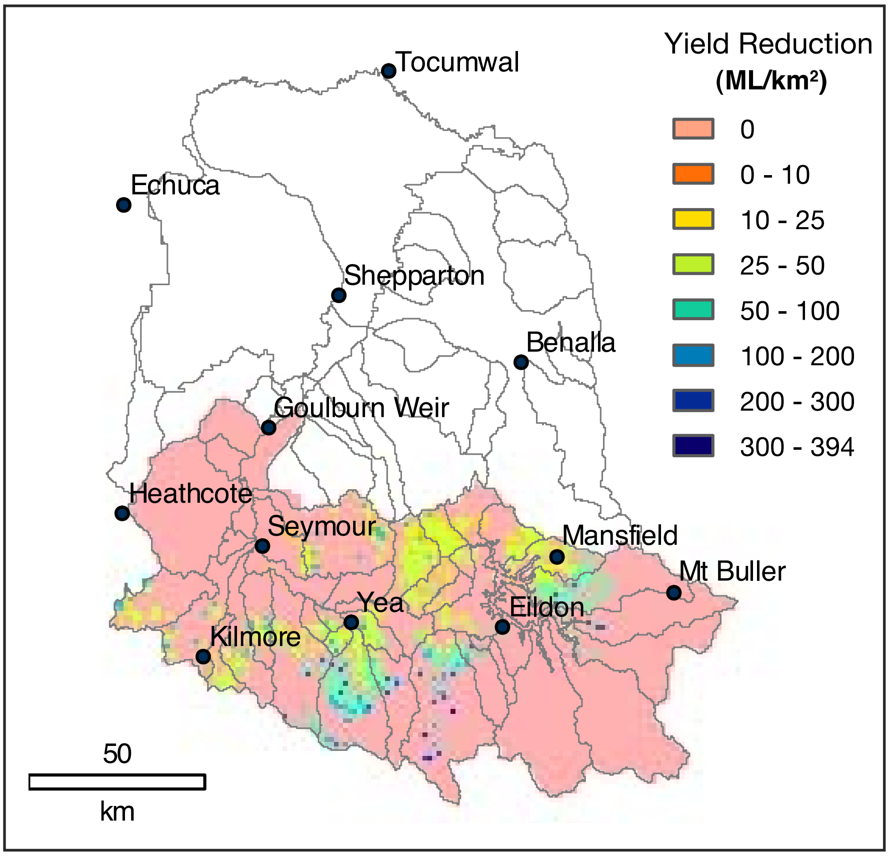

Figure 15. Reduction in water yield or stream flow based on *medium* moderate scenerios.

variability. To quantify the impact of landuse change on flows, one needs to remove the effect of rainfall. This requires further investigation and is beyond the scope of this study. The method developed by Lane *et al.* (2002) can potentially be used for this purpose, but it needs further testing. An alternative method is to use a nearby catchment with no landuse change as a reference for detecting the effect of rainfall variability on runoff. In this case, stream flow data from Mollision Creek were used. The catchment area is 163 km^2 with a stable mixture of land-use (forest and grazing). The flow was divided into two periods 1989-1991 and 1998-2000 to coincide with the flow from Pine Creek. It is clear that the differences in flow were very small between these two periods for Mollison Creek (Figure 16a). As a result, the large differences in flows for Pine Creek can be attributed mainly to landuse changes.

For monthly flows, the difference in flow reduction between low flows and high flows is less significant as shown in Figure 16b. These relationships provided the basis for a simple model described in Section 2.5 that can be used in conjunction with the mean annual model for estimating afforestation impact on seasonal flows.

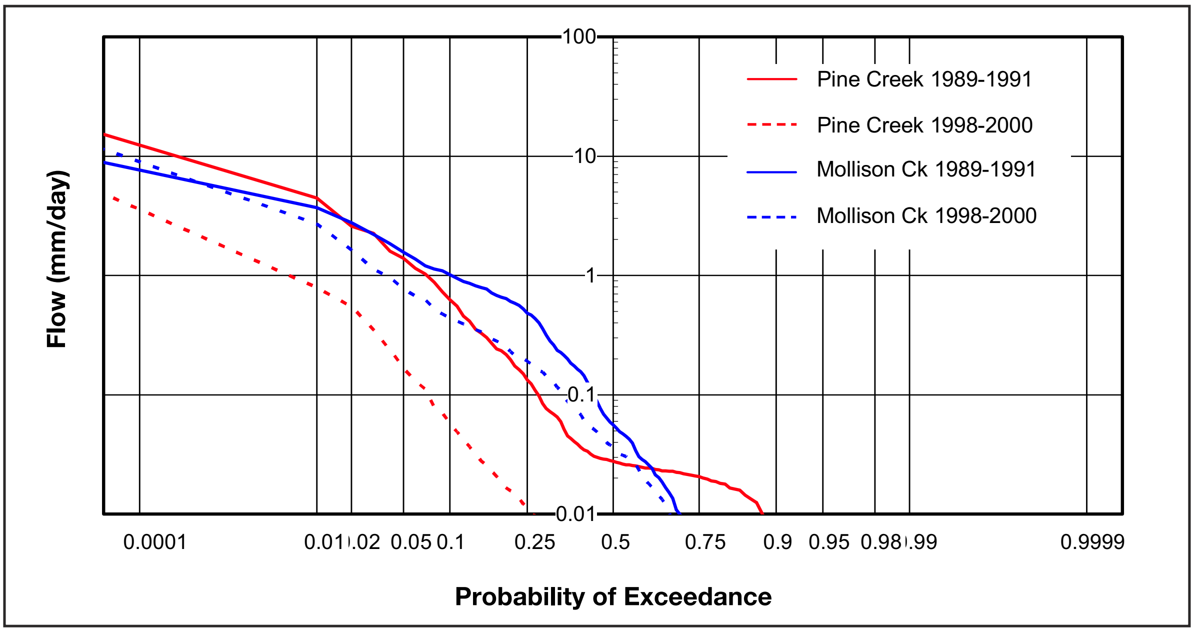

Figure 16a. Daily flow duration curves for Pine Creek and Mollison Creek catchments. The solid lines represent daily flows for the period of '89-'91 and the dotted lines represent daily flows for the period of '98-2000.

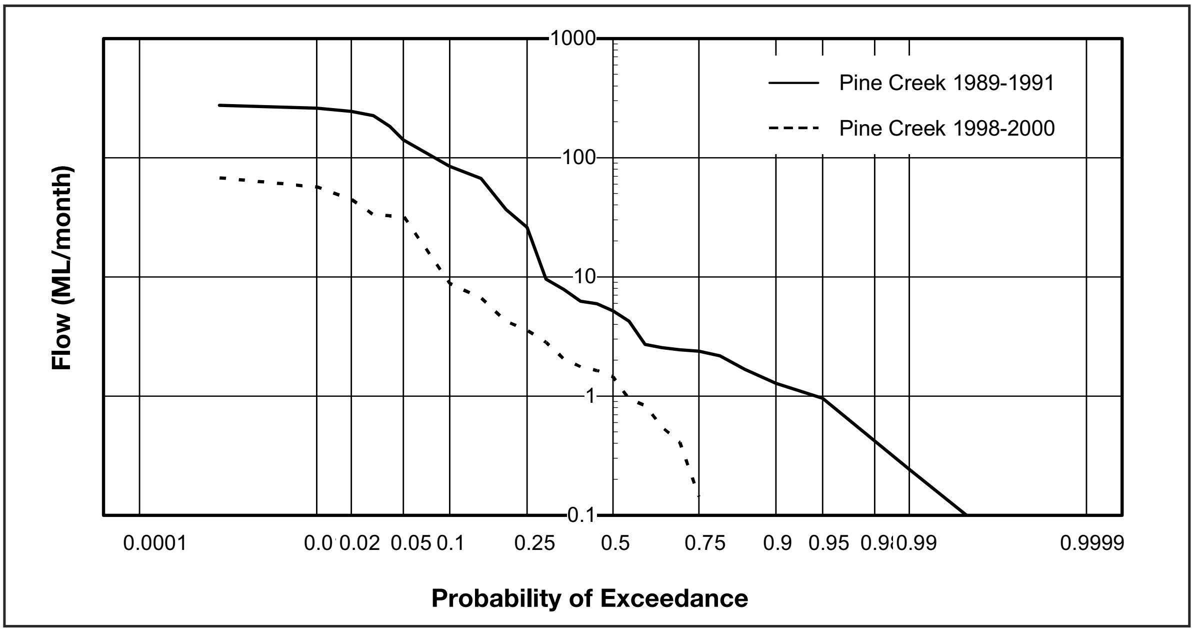

Figure 16b. Monthly flow duration curves under grass (solid line) and pine (dotted line) for Pine Creek catchment.

Figure 17 shows the FDCs for Goulburn Weir under current land-use conditions, the *maximum* and the *moderate* scenarios. Clearly, changes in seasonal flows at Goulburn Weir are less significant than the changes at the Pine Creek. The results shown in Figure 17 suggest that high flows under the *moderate* blue gum plantation scenario will be reduced by 15%, while the reduction in low flows could be as high as 40%. For the *moderate* scenario, there is imperceptible change to high flows, but for medium to low flows, the flow reduction increases markedly as flow decreases and follows the *maximum* scenario more closely.

4.4 Impact of Blue Gum Plantation Establishment on Water Supply

The system simulation model of the Goulburn water supply system (GSM) used in defining the Goulburn Bulk Water Entitlement (BE) (Water Bureau, 1995) was used to estimate the impacts of afforestation identified in this study on water supply in the Goulburn system. Use of the GSM allows the complex interactions between inflow rates and volumes, harvesting in both on-stream and off-stream storages, and water supply to be assessed. The model simulates operation of the Goulburn/Broken/Loddon and Campaspe water supply systems using inflow and climatic data for the period 1891 – 1993. Model outputs include time series of irrigation deliveries, water available for use, and streamflow.

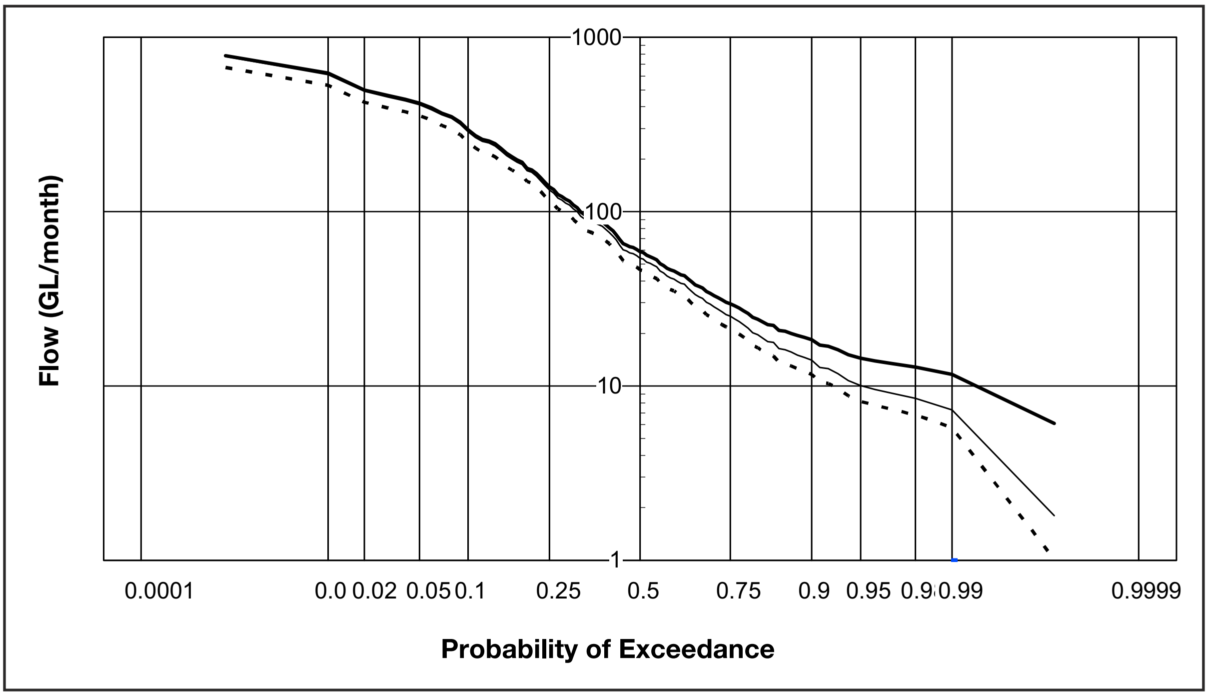

Figure 17. Monthly flow duration curves for Goulburn Weir under current conditions (thick line), the *maximum* scenario (dashed line) and the *moderate* scenario (thin line).

Goulburn System gravity irrigation customers hold a 'Water Right', which effectively provides access to two separate water products. The first is the water right. The system is managed to provide this with a high reliability, that is, in almost all years. The second is the sales component, which is made available in varying quantities when there are sufficient resources to provide the water right in the following season under minimum inflow conditions. Throughout each season, water available for use is progressively declared by way of the "seasonal allocation", which expresses in terms of percentage how much of the water right is available for delivery. A seasonal allocation of 100% corresponds to all the water right being available, but no sales. A seasonal allocation of 200% is equivalent to 100% of the water right being available, plus the maximum of 100% sales.

Figure 18 shows the predicted impact of the afforestation scenarios on Goulburn system irrigation security (where security is the reliability of the seasonal water allocation). This shows that the percentage of time final seasonal water allocations to irrigators is less than 100% of the water right would increase from 3% under current conditions to 5% and 7% in the *moderate* and *maximum* plantation scenario, respectively.

The GSM also predicts that average deliveries of irrigation water in the irrigation districts would decrease by 1.5% in *moderate* plantation scenario, and 4.9% in the *maximum* plantation scenario. Any alteration of the bulk water entitlement (BE) to reduce detrimental environmental impacts of afforestation would further reduce average deliveries and security.

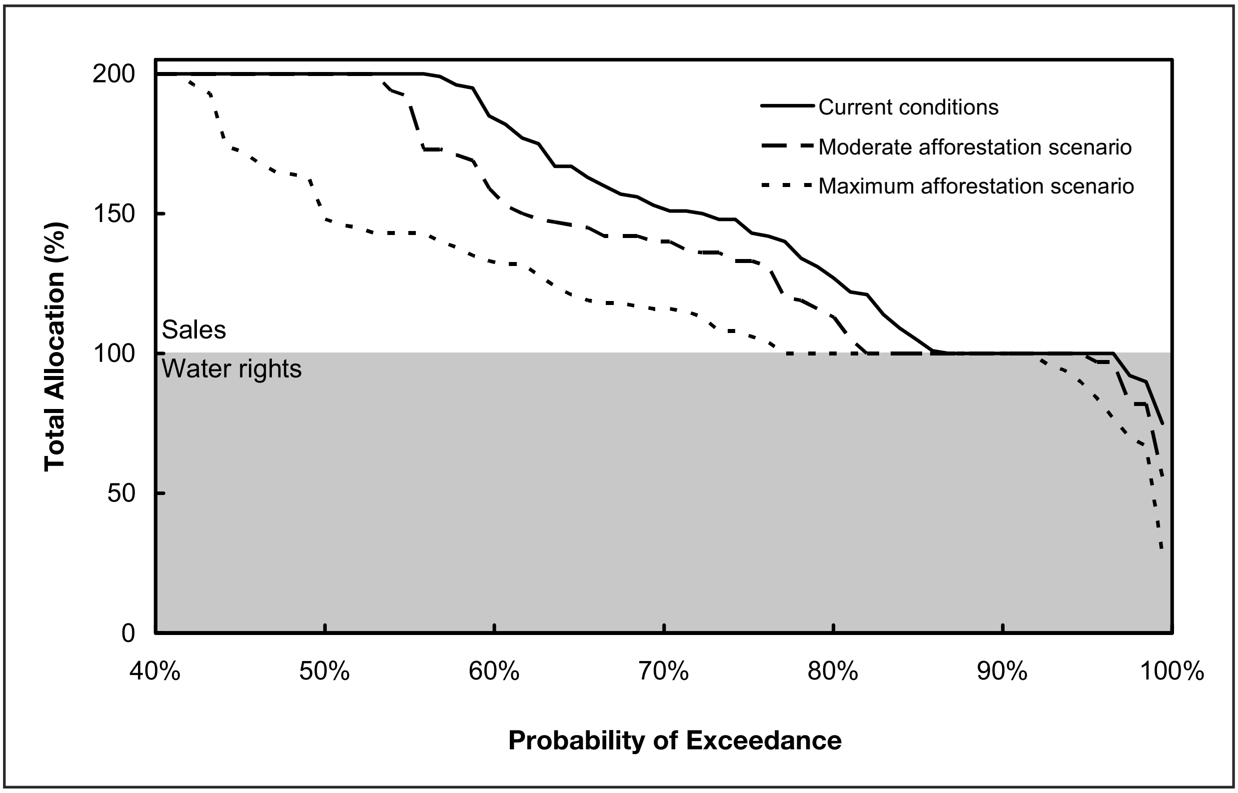

Figure 18. The predicted effect of two bluegum afforestation scenarios on the reliability of water allocations in the Goulburn-Broken system. Note that allocations are committed to a 200% level under the Victorian system, with the first 100% representing allocations against water rights, and the remainder against sales.

4.5 Impact on Winter and Spring Unregulated Flows and Environmental Releases

The Goulburn BE, which sets out the rights of the Goulburn-Murray Rural Water Authority to take water from the Goulburn River, preserves environmental values by limiting the extraction of water from the river. The BE also specifies inflow conditions under which special releases at high rates from Lake Eildon for environmental purposes must be made, and inflow conditions under which minimum release rates must be increased. The current BE was established in 1995, and is based on the inflow environment that existed at that time. In other words, it does not allow for the impact of climate change or land use change on inflows.

The change in the average quantity of unregulated flow past Goulburn Weir (which is influenced by releases from Lake Eildon) in spring can be used as a simple measure of the impact of afforestation on environmental flows. The modelling showed that under the current BE and the *moderate* scenario, unregulated flows would decrease by an average of 6%. Under the *maximum* plantation development scenario, unregulated flows would decrease by an average of 27%. The impacts of afforestation on environmentally useful unregulated flow would be proportionally greater than on extractive supplies because the water harvesting and storage works regulate water up to their physical and regulatory limits. The reduction in catchment yield, ie, inflows to water harvesting works or storages, would therefore have a greater impact on the unregulated water than on the regulated, harvested water.

5. Discussion and Summary

The accuracy of the simple water balance model depends on rainfall and forest cover estimates. In this study, mean annual rainfall was obtained from the Bureau of Meteorology and the use of this dataset may be appropriate for catchments with little topographic effect on rainfall. However, it may present a problem for catchments in the headwaters of the Goulburn River where the topographic effect may be significant. It should also be noted that the simple water balance model does not consider the effect of snowfall on evapotranspiration and hence there may be noticeable errors in predicted evapotranspiration for catchments where snowfall is a large proportion of total precipitation. Forest cover is the other input that can affect the accuracy of the water balance model. We relied on the vegetation data derived by Ritman (1995) and this provided a woody vegetation cover status in 1991. With these inputs, the simple water balance model can explain most of the measured variation in mean annual stream flow for 16 sub-catchments within the Goulburn-Broken. It is also shown that the model estimates of inflow to Lake Eildon and Goulburn Weir (including Lake Eildon) are in good agreement with observed data.

This study has focused on the impact of blue gum plantation on annual flow regime and water yield. The maximum area identified as suitable for blue gum plantation represents 16% and 21% of the total catchment area above Lake Eildon and Goulburn Weir (including Lake Eildon), respectively. Under the *maximum* plantation scenario, the estimated reductions in mean annual flow to Lake Eildon and Goulburn Weir are 113 and 400 GL per year. These reductions are significant, representing 8% and 14% of current mean annual flow. However, it should be noted that this is a worst case scenario based on the assumption that the whole area suitable will become plantations. It is clear that there are other factors, such as infrastructure, social and economic, that can significantly limit plantation expansion.

Under the *moderate* scenario, estimated reduction in mean annual flow is 27 GL per year or 2% and 105 GL per year or 4% for Lake Eildon and Goulburn Weir, respectively. Under the low adoption scenario, 10% plantation adoption rate in suitability classes 1 and 2, the reduction in mean annual flow is only 3 GL per year or 1% and 56 GL per year or 2% for Lake Eildon and Goulburn Weir, respectively. In all scenarios, the greatest yield reduction occurs in the catchments with most suitable land and therefore a greater percentage of new tree plantations. The least affected areas coincide with the least suitable land, therefore the least plantations. In the vicinity of Goulburn Weir, land, although cleared, is generally too dry to be suitable for blue gum plantations, while above Lake Eildon, it is mostly tree covered.

It is clear that while the predicted reduction in stream flow is affected by rainfall, current land-use, and the underlying assumptions of the model, the results are influenced even more significantly by the adoption scenarios. Irrespective of the adoption rate chosen, there will be an establishment and harvesting cycle which will keep the actual plantation area below the estimated area. Evaluating the current land-use and developing more realistic scenarios will make the model predictions more relevant for catchment management.

Reductions in annual flow increase as trees within plantations grow and studies from South Africa suggest that it may take 5 to 10 years for catchments under Eucalyptus plantations to establish a new equilibrium (Scott and Smith, 1977). Information on the time to maximum impact is important when evaluating the economic and social impact of afforestation. In this study, the time to maximum impact was predicted using the results from 3PG modelling, a crucial step forward in making the water yield reduction estimate more realistic. The underlying assumption is that tree water use is directly related to leaf area index and would increase with tree age until maximum water use is achieved. For the Goulburn-Broken catchment, modelling results from 3PG suggest that it will take 8 to 16 years for blue gum plantations to reach their maximum water use and hence maximum stream flow reduction.

Our understanding of the afforestation impact on annual flow regime is limited. However, it is possible to draw some general conclusions about the impact of afforestation on high flow or stormflow and low flow or dry-season flow. Afforestation is expected to decrease stormflow volumes and the magnitude of peak flows by removing a proportion of the storm rainfall and accumulating soil water storage. These effects are most significant for small storms and least significant for large storms. Most experimental evidence suggests that afforestation can significantly reduce dry-season flow to the extent of drying up streams completely. This is because trees can sustain relatively high transpiration rates during the dry season and hence create large soil water deficits. Percentage reductions in dry-season flow as a result of afforestation are generally greater than the reductions in stormflows, although the latter will have much greater impact on total volume reduction.

We have attempted to evaluate the impact of blue gum plantation establishment on annual flow regime using flow duration curve analysis. Based on observed responses described above from paired catchment studies, it is assumed that reductions in percentile flows following plantations can be represented by a combination of a proportional reduction and a constant reduction in flows. This method assumes that responses obtained from paired catchments can be scaled up to large catchments and does not require detailed data or intensive modelling. It is a simple statistical method that appears to give sensible results. However, it should also be noted that the model was locally calibrated and hence the results should not be extrapolated outside the region as the coefficients may change with climate and catchment characteristics. The method requires further testing and refinement before being operationalised in catchment management.

By using this method, it is estimated that if the total area suitable for blue gum plantations were developed, there would be 15% and 40% reductions in high and low flows at Goulburn Weir, respectively. This flow reduction would have a significant impact on water supply security and deliveries, and on environmental flows. However, given that the likely adoption rates will be lower, the impacts of plantation establishment on water supply are expected to be scaled down.

This study also attempted to evaluate the impact of blue gum plantation establishment on water allocation and it is estimated that the percentage of time final seasonal water allocations to irrigators are less than 100% of the water right would increase from 3% under current conditions to 7% in the *maximum* plantation scenario. The average deliveries of irrigation water in the irrigation districts would decrease by 1.5% in *moderate* plantation scenario, and 4.9% in the *maximum* plantation scenario. The modelling also showed that under the current BE and the *moderate* scenario, unregulated flows would decrease by an average of 6%. Under the *maximum* plantation development scenario, unregulated flows would decrease by an average of 27%.

Afforestation has a number of environmental benefits including reduced groundwater recharge, biodiversity, and carbon sequestration. However, these benefits will come at the expense of reduced streamflows or water yield. Given our commitment to increased environment flows and water security, this will exert additional pressure on our water resource system. Future afforestation development should be considered within a catchment management framework whereby the benefits and negative effects associated with afforestation are evaluated in order to achieve optimum outcomes.

References

Best, A., Zhang, L., McMahon, T., Western, A., and Vertessy, R. (2003). A critical review of paired catchment studies with reference to the seasonal flows and climate variability, CRC for Catchment Hydrology Technical Report 03/4, Murray-Darling Basin Commission.

Bradford, A., Zhang, L., Hairsine, P. (2001). Implementation of a mean annual water balance model within a GIS framework and application to the Murray-Darling Basin. Technical Report 01/8. Cooperative Research Centre for Catchment Hydrology.

Centre for Land Protection Research (2000). Goulburn Broken Dryland Regional Development Projects, Land and Climatic Suitability Criteria.

Department of Primary Industries and Energy (1997). The 2020 Vision Statement. Commonwealth of Australia, Canberra, ACT.

Goulburn Broken Catchment Management Authority (1998). Catchment Strategy.

Holmes, J.W., and Sinclair, J.A., (1986). Water yield from some afforested catchments in Victoria, Hydrology and Water Resources Symposium, Griffith University, Brisbane, 25-27 November 1986. The Institution of Engineers, Australia.

Houlder, D.J., Hutchinson, M.F., Nix, H.A. and McMahon, J.P. (1999). ANUCLIM User Guide, Version 5.0. Centre for Resource and Environmental Studies, Australian National University, Canberra.

Hughes, D.A., Smakhtin, V. (1996). Daily flow data time series patching or extension: a spatial interpolation approach based on flow duration curves. Hydrol. Sci. J. 41(6), 851-871.

Landsberg, J.J. and Waring, R.H. (1997). A generalized model of forest productivity using simplified concepts of radiation-use efficiency, carbon balance and partitioning. Forest Ecology and Management 95: 209-228.

Lane, P., Hickel, K., Best, A. and Zhang, L. (2003). The effect of afforestation on annual streamflow regime. CRC for Catchment Hydrology Technical Report 03/6, Murray-Darling Basin Commission.

Linke, G.K., Seker, M. and Livingston. M. (1995). Effect of reafforestation on stream flows, salinities and groundwater levels in the Pine Creek catchment. Murray Darling 1995 Workshop Extended abstracts, Wagga Wagga, Australia. 11-13th September 1995. 175-178.

Monteith, J.L.(1981). Evaporation and surface temperature. Q.J.R. Meteorol. Soc., 107, 1-27.

Morris, J.D. (1999). Further development of the 3PG forest growth model and application to young eucalypt stands in Victoria. Centre for Forest Tree Technology Report No 99/058.

Ritman K.T, (1995) Structural Vegetation Data: a specification manual for the Murray Darling Basin Project M305.Murray-Darling Basin Commission, Canberra, ACT.

Sivapalan, M., Ruprecht, J.K., and Viney, N.R. (1996). Water and salt balance modelling to predict the effects of land-use changes in forested catchments. 1. Small catchment water balance model. Hydrological Processes, 10, 393-411.

Scott, D.F. and Smith, R.E. (1997). Preliminary empirical models to predict reduction in total and low flows from afforestation. Water SA, 23(2), 135-140.

Trapnell, L. (unpublished) Economics and cash flow from tree crops for restoring hydrological balance in high rainfall areas. Unpublished report. Natural Resources and Environment, Benalla, Victoria, Australia.

Turner, K.M., Annual evapotranspiration of native vegetation in a Mediterranean-type climate. Water Resour. Bull., 27, 1-6, 1991.

Vertessy, R.A. and Bessard, Y. (1999). Anticipating the negative hydrological effects of plantation expansion: Results from a GIS-based analysis on the Murrumbidgee Basin. In: J. Croke and P. Lane (eds.), Forest Management for the protection of water quality and quantity. Proceedings of the 2nd Erosion in Forests Meeting, Warburton, 4-6 May 1999, Cooperative Research Centre for Catchment Hydrology, Report 99/6, pp 69-73.

Vertessy, R.A., Rahman J, Bessard, Y, and Zhang, L. (2000). The impacts of afforestation on water yield: predictions using MAYA. Water, 27(6): 16-19.

Water Bureau, Department of Conservation and Natural Resources Victoria (February 1995). Goulburn Simulation Model – Base Run 0600 Specification. Bulk Water Entitlements Report Series. Report No. 3.

Zhang, L., Dawes,W.R. and Walker, G.R. (1999). Predicting the Effect of Vegetation Changes on Catchment Average Water Balance. Technical Report 99/12, CRC for Catchment Hydrology.

Zhang, L., Dawes, W.R., and Walker, G.R., (2001). Response of mean annual evapotranspiration to vegetation changes at catchment scale. Water Resources Research, 37, 701-708.

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- Department of Sustainability and Environment, Vic
- Goulburn-Murray Water
- Griffith University
- Melbourne Water
- Monash University
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- Natural Resources and Mines, Qld
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